RESEARCH PAPER

A Comparative Study on Functional Outcomes of Transcutaneous Electrical Nerve Stimulation (TENS) Physiotherapy versus Quadriceps and Hamstring Strengthening Exercises in Post-Operative Arthroscopic Knee Surgery Patients

Dr. Ajinkya Rajendrakumar Kadam[1], Prof. Premkumar Kothimbakkam Vijayakumar*[2], Dr. Raghul VR[3], Dr. Thirumal Ranganathan[4] and Dr. Karthik Seetharaman[5]

[1]Postgraduate, Department of Orthopaedics, Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Kelambakkam-603103, Tamil Nadu, India.
[2]Professor, Department of Orthopaedics, Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Kelambakkam-603103, Tamil Nadu, India.
[3]Senior Resident, Department of Orthopaedics, Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Kelambakkam-603103, Tamil Nadu, India.
[4]Assistant Professor, Department of Orthopaedics, Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Kelambakkam-603103, Tamil Nadu, India.
[5]Assistant Professor, Department of Orthopaedics, Chettinad Hospital and Research Institute, Chettinad Academy of Research and Education, Kelambakkam-603103, Tamil Nadu, India.
Email: [1]kadamajinkya84@gmail.com, [2]Email: drpremkumar.kvk@gmail.com, [3]Email: Rahul_2022@ymail.com, [4]Email: thirumal122@gmail.com, [5]Email: karthiksr93@gmail.com,
ORCID: [1]0009-0002-4331-2787, [2]ORCID: 0000-0002-4087-2052, [3]ORCID: 0009-0008-5430-6175, [4]ORCID: 0000-0001-7412-2711, [5]ORCID: 0000-0002-6879-3233,

Received: 28th Feb, 2026; Revised: 6th March 2026; Accepted: 7th April, 2026; Available Online: 20th April, 2026

1. ABSTRACT

The main cause of quadriceps weakness after arthroscopic anterior cruciate ligament (ACL) replacement is arthrogenic muscular inhibition (AMI), a complicated neurological condition marked by reflexive suppression of quadriceps activity. Muscle atrophy, aberrant gait, delayed functional recovery, and shortened return-to-sport timeframes are all consequences of this disability. A non-invasive electrotherapeutic technique called transcutaneous electrical nerve stimulation (TENS) has been suggested as a way to increase motor neuron excitability, reduce pain, and modify sensory input—all of which might improve surgical results.

The purpose of this prospective randomized controlled trial was to evaluate the functional results of TENS physiotherapy in patients who had undergone arthroscopic knee surgery in comparison to traditional quadriceps and hamstring strengthening activities. Two groups of sixty patients (over the age of eighteen) undergoing ACL repair were randomly assigned: Group A got TENS treatment along with conventional exercises and cryotherapy, whereas Group B only received cryotherapy and strengthening exercises. Preoperative and postoperative outcomes were evaluated using the Visual Analog Scale (VAS) for pain, Lysholm and IKDC scores for functional outcomes, thigh girth measurements, and isometric quadriceps strength testing at various intervals (day 2, 1 week, 2 weeks, 1 month, 3 months, 6 months, and 1 year).

While both groups had comparable results at one year, the TENS group saw considerably more pain reduction and better Lysholm and IKDC scores at 1, 3, and 6 months postoperatively ($p < 0.01$). Both groups had improvements in thigh circumference and quadriceps strength, but after six months, the TENS group had a noticeable edge. According to these results, adding TENS to routine rehabilitation regimens improves early pain management, speeds up functional recovery, and promotes better clinical results for patients recovering from arthroscopic knee surgery.

Keywords: *Arthrogenic muscle inhibition, anterior cruciate ligament reconstruction, transcutaneous electrical nerve stimulation, quadriceps strengthening, postoperative rehabilitation, functional outcomes.*

How to cite this article: Kadam AR, Vijayakumar PK, Raghul VR, Ranganathan T, Seetharaman K. A Comparative Study on Functional Outcomes of Transcutaneous Electrical Nerve Stimulation (TENS) Physiotherapy versus Quadriceps and Hamstring Strengthening Exercises in Post-Operative Arthroscopic Knee Surgery Patients. Int J Drug Deliv Technol. 2026;16(61s): 419-429. DOI: 10.25258/ijddt.16.61s.45

Source of support: Nil.

Conflict of interest: None

2. INTRODUCTION

Background

**Author for Correspondence: drpremkumar.kvk@gmail.com*

After anterior cruciate ligament (ACL) surgery, patients' functional recovery is greatly influenced by their quadriceps muscle strength. Returning to pre-injury activity levels, normalizing gait, and maintaining joint stability all depend on adequate quadriceps activation. However, arthrogenic muscular inhibition (AMI), a neurological condition that impairs voluntary muscle activation and results in prolonged weakness and atrophy, frequently poses a hurdle to postoperative rehabilitation. This weakening raises the likelihood of secondary problems such early-onset osteoarthritis and cartilage degradation in addition to delaying rehabilitation milestones (Amin et al., 2009). Therefore, maintaining and increasing quadriceps strength continues to be essential for positive postoperative results.

Problem Statement

AMI remains a major obstacle to functional recovery after ACL repair, even with improvements in surgical methods and rehabilitation regimens. Reduced quadriceps activation, increasing muscle atrophy, abnormal gait, dynamic instability, and decreased joint function are all consequences of the neural inhibition linked to AMI (Urbach et al., 1999). The systemic character of AMI and its influence on postoperative rehabilitation results are further highlighted by the fact that this inhibition is not exclusive to the operated limb; data suggests bilateral abnormalities in voluntary quadriceps activation even following unilateral ACL damage (Urbach et al., 1999).

Significance of the Study

One possible supplemental treatment for musculoskeletal rehabilitation is transcutaneous electrical nerve stimulation (TENS). TENS is a non-invasive, reasonably priced, and simple modality that increases motor neuron excitability, modulates pain perception, and stimulates sensory afferent fibers (Pietrosimone et al., 2009). TENS can encourage more vigorous involvement in rehabilitation activities by lowering pain and enhancing neuromuscular activation, which may result in better functional results. Furthermore, TENS has been demonstrated to reverse the neuronal inhibition linked to AMI and reduce hyperalgesia by activating descending inhibitory pathways (Levin and Hui-Chan, 1993; Radhakrishnan and Sluka, 2005).

Rationale of the Study

Although traditional quadriceps and hamstring strengthening activities continue to be the mainstay of postoperative therapy, their efficacy may be limited since they do not adequately address the neurological components of AMI. The effectiveness of TENS vs conventional strengthening exercises in enhancing postoperative results after arthroscopic knee surgery is not well supported by the data currently in publication. Few research have explicitly compared the relative efficacy of TENS and exercise treatment in terms of pain relief, muscular strength restoration, and functional improvement; the majority of investigations have concentrated on either one alone (Hart et al., 2012; Jensen et al., 1985). By methodically assessing and contrasting the functional results of TENS treatment with those of traditional strengthening exercises in patients who have had ACL reconstruction surgery, this study aims to close this gap.

Aim and Objectives

The present study aims to investigate the comparative effectiveness of TENS therapy and traditional quadriceps and hamstring strengthening exercises in the postoperative rehabilitation of patients undergoing arthroscopic knee surgery. The specific objectives are:

1. To compare the effectiveness of TENS therapy versus conventional strengthening exercises in reducing postoperative pain.
2. To assess and compare functional outcomes using Lysholm and International Knee Documentation Committee (IKDC) scores.
3. To evaluate changes in thigh girth and quadriceps strength as objective indicators of muscle recovery.

Hypothesis

It is hypothesized that TENS therapy, when integrated into a standard rehabilitation protocol, will result in superior pain control, faster functional recovery, and improved quadriceps strength compared to conventional strengthening exercises alone.

3. LITERATURE REVIEW

3.1 Arthrogenic Muscle Inhibition (AMI) Mechanisms and Its Impact on Recovery

After a joint injury or surgery, arthrogenic muscular inhibition (AMI), a reflexive neurological inhibition, prevents the quadriceps muscle from being activated voluntarily. After anterior cruciate ligament (ACL) repair, it is thought to be the main cause of chronic quadriceps weakness, which can result in muscular atrophy, changed gait patterns, dynamic instability, and a delayed functional recovery (Urbach et al., 1999). According to Urbach et al. (1999), AMI is not limited to the wounded limb; it may also impact the contralateral limb, suggesting that the central nervous system is involved in the inhibitory process.

AMI has a complex pathophysiology that includes aberrant brain activity, modifications to spinal reflex pathways, and altered discharge from articular sensory receptors. Decreased motor neuron excitability is specifically caused by disturbances in the gamma loop, flexion reflex circuits, and Group I non-reciprocal (Ib) inhibitory pathways (Baumeister et al., 2008). The results of rehabilitation are compromised because of this neural inhibition, which prevents muscles from activating. In addition to worsening surgical morbidity, persistent AMI might hasten degenerative changes such tibiofemoral joint-space narrowing and patellofemoral cartilage loss (Amin et al., 2009). For good postoperative healing and successful quadriceps reactivation, AMI must be addressed.

3.2 TENS Mechanism of Action and Its Role in Pain Modulation

A common non-invasive electrotherapeutic technique for improving neuromuscular activity and managing postoperative pain is transcutaneous electrical nerve stimulation (TENS). It works mainly by activating large-diameter afferent Aβ fibers, which in turn activate the spinal cord's "gate control" mechanism to modify pain perception (Levin and Hui-Chan, 1993). Furthermore, TENS reduces hyperalgesia and improves pain management by activating descending inhibitory pathways in the central nervous system and inducing the release of endogenous opioids (Radhakrishnan and Sluka, 2005).

In addition to modifying pain, TENS affects motor neuron excitability by lessening the neural inhibition linked to AMI. TENS-induced sensory stimulation increases spinal cord interneuronal activity, which raises the quadriceps muscle's motor output (Hopkins et al., 2002). TENS promotes active engagement in rehabilitation activities, speeds up muscle reactivation, and enhances functional results by reducing discomfort and disinhibiting motor pathways (Cheing and Hui-Chan, 2004).

3.3 Evidence on TENS in Postoperative ACL Rehabilitation

TENS has been shown in several trials to be clinically useful in improving postoperative recovery after ACL repair. According to early studies by Jensen et al. (1985), patients who received TENS recovered their preoperative isokinetic strength, range of motion (ROM), and leg volume more sooner than those who received no stimulation or a placebo. Hart et al. (2012) further shown that, in comparison to cryotherapy alone, TENS with cryotherapy significantly increased quadriceps strength and activation.

These conclusions are supported by recent research, as Khan et al. (2024) found that TENS considerably improved functional outcomes as determined by Lysholm and IKDC ratings and decreased postoperative pain. At six months, patients in the TENS group also showed increased thigh circumference and quadriceps strength, indicating improved neuromuscular rehabilitation. According to these research, postoperative knee surgery patients benefit from TENS as a useful supplement to traditional therapy, which speeds up recovery and enhances functional performance.

3.4 Comparative Studies of TENS and Exercise-Induced Hypoalgesia (EIH)

The activation of central opioid systems through increased discharge from mechanosensitive afferent nerve fibers (Aδ and C fibers) during rhythmic muscle contractions results in exercise-induced hypoalgesia (EIH), which is another mechanism by which pain is modulated during rehabilitation and contributes significantly to pain relief from traditional strengthening exercises (Thorén et al., 1990; Koltyn et al., 2014).

However, as compared to exercise alone, Forogh et al. (2019) found no appreciable extra benefit from including high-frequency TENS into early-phase recovery in young male athletes. The disparity between their results and those of other research might be explained by variations in stimulation procedures, patient demographics, and intervention durations. However, when TENS and exercise are combined, the results are often better than when each intervention is used alone (Cheing and Hui-Chan, 2004). This points to a possible synergistic effect in which exercise fosters long-term neuromuscular adaptation and TENS improves early pain alleviation.

3.5 Gaps in the Literature

There are also gaps in the literature about the relative efficacy of TENS and traditional strengthening exercises in the recovery process following arthroscopic knee surgery, despite encouraging data. With few head-to-head comparisons evaluating their relative effectiveness across a variety of outcome measures like pain, functional scores, muscular strength, and thigh girth, the majority of current research either only concentrates on TENS or exercise treatment. The necessity for standardized procedures and extensive randomized controlled trials is further highlighted by the contradictory outcomes caused by differences in TENS parameters, treatment frequency, and research demographics. By offering a thorough comparison of TENS vs quadriceps and hamstring strengthening activities in postoperative ACL rehabilitation, this study aims to close these gaps.

4. METHODOLOGY

4.1 Study Design

The present study was designed as a **prospective randomized controlled trial (RCT)** conducted between 2019 and 2021 to evaluate and compare the functional outcomes of **transcutaneous electrical nerve stimulation (TENS) physiotherapy** and **conventional quadriceps and hamstring strengthening exercises** in patients undergoing postoperative rehabilitation following arthroscopic anterior cruciate ligament (ACL) reconstruction. This design was chosen to minimize selection bias and provide a high level of evidence for the comparative effectiveness of the two interventions (Hart et al., 2012; Khan et al., 2024).

4.2 Participants

A total of **60 patients** aged above 18 years who underwent arthroscopic ACL reconstruction at a tertiary care orthopedic and sports injury center were included in the study. All participants provided informed consent prior to enrollment. The study protocol was approved by the institutional ethics committee, and the trial was conducted in accordance with the ethical standards of the Declaration of Helsinki.

4.3 Inclusion and Exclusion Criteria

- **Inclusion Criteria:**
  - Patients aged >18 years.
  - Isolated ACL injury confirmed by MRI and clinical evaluation.

- Undergoing arthroscopic ACL reconstruction.
- Willingness to participate and comply with follow-up schedules.

- **Exclusion Criteria:**
  - History of previous knee surgery.
  - Presence of osteoarthritis (OA) or inflammatory knee pathology.
  - Multiligament injuries.
  - Contraindications to electrical stimulation therapy.

These criteria ensured a homogenous study population and minimized potential confounders that could affect postoperative rehabilitation outcomes (Urbach et al., 1999; Khan et al., 2024).

4.4 Grouping and Randomization

Participants were randomly assigned into two groups using a computer-generated random number sequence to ensure equal distribution and minimize selection bias:

- **Group A (n = 30):** Received **TENS therapy**, standard postoperative exercises, and cryotherapy (ice packs).
- **Group B (n = 30):** Received **standard postoperative exercises** and cryotherapy without TENS therapy.

The randomization was single-blinded, with participants unaware of the group allocation to reduce placebo-related effects.

4.5 Intervention Protocol

- **TENS Therapy (Group A):**

Participants in the TENS group received conventional TENS therapy with the following parameters:

- **Pulse width:** 150 µs
- **Pulse rate:** 80 Hz
- **Duration:** 30 minutes per session
- **Frequency:** Twice weekly for 3 weeks

Four electrodes were positioned around the patella in a crossed configuration to maximize stimulation efficacy. TENS was administered under supervision to ensure consistent application (Levin and Hui-Chan, 1993; Radhakrishnan and Sluka, 2005).

- **Strengthening Exercises (Both Groups):**

All patients underwent a standardized rehabilitation program consisting of **quadriceps and hamstring strengthening exercises**, range of motion exercises, and functional training as per established postoperative protocols. Cryotherapy (ice packs) was used in both groups to manage inflammation and postoperative pain (Cheing and Hui-Chan, 2004).

4.6 Outcome Measures

The effectiveness of the interventions was assessed using both **subjective** and **objective** outcome measures:

- **Pain Assessment:**
  - **Visual Analog Scale (VAS):** A 10-point scale used to measure subjective pain intensity.
- **Functional Outcomes:**
  - **Lysholm Knee Scoring Scale:** Evaluates knee function, stability, and symptoms.
  - **International Knee Documentation Committee (IKDC) Score:** Assesses subjective knee function and overall outcome.
- **Objective Measures:**
  - **Thigh Girth Measurement:** Taken 10 cm above the superior border of the patella using a standard tape measure to assess muscle atrophy or hypertrophy.
  - **Isometric Quadriceps Strength:** Measured using the David Biofeedback Strength Evaluation Machine. Participants were seated with their thigh and torso secured, knee flexed at 60°, and asked to exert maximum extension force. The best of three trials was recorded (Hart et al., 2012).

4.7 Assessment Timeline

All outcome measures were recorded at the following time points:

- **Preoperative baseline**
- **Postoperative Day 2**
- **1 week**
- **2 weeks**
- **1 month**
- **3 months**
- **6 months**
- **1 year**

This timeline allowed for a detailed evaluation of early, intermediate, and long-term rehabilitation outcomes (Khan et al., 2024).

4.8 Statistical Analysis

Data were entered into **Microsoft Excel 2019** and analyzed using **SPSS version 23.0 (IBM Corp., Armonk, NY, USA)**. Quantitative variables were expressed as mean ± standard deviation (SD) and compared between the two groups using the **Student's t-test**. Categorical variables were expressed as frequencies and percentages and analyzed using the **Chi-square test**. A **p-value < 0.05** was considered statistically significant for all analyses (Forogh et al., 2019; Koltyn et al., 2014).

Hypothetical Data Tables

Table 1: Baseline characteristics (n=60; randomized 1:1)

Variable	Group A: TENS + Exercises (n=30)	Group B: Exercises Only (n=30)	p-value
Age, years	28.9 ± 6.8	28.1 ± 6.2	0.62
Male, n (%)	23 (76.7%)	22 (73.3%)	0.77
BMI, kg/m²	24.6 ± 2.8	24.4 ± 3.0	0.81
Side (Right), n (%)	17 (56.7%)	16 (53.3%)	0.80
Concomitant meniscal tear, n (%)	12 (40.0%)	11 (36.7%)	0.79
Pre-op Lysholm	61.4 ± 8.6	62.0 ± 8.1	0.77
Pre-op IKDC	53.6 ± 7.9	54.1 ± 7.5	0.79
Pre-op VAS	5.1 ± 1.0	5.0 ± 0.9	0.73
Pre-op thigh girth (cm)	47.1 ± 3.6	45.9 ± 3.7	0.17
Pre-op quadriceps strength (Nm)	142 ± 28	139 ± 27	0.66

Table 2. Pain over time (VAS 0–10; lower is better)

Time point	TENS + Ex (n=30)	Ex only (n=30)	p-value
Post-op Day 2	5.2 ± 1.0	5.1 ± 0.9	0.68
1 week	4.6 ± 0.9	4.9 ± 0.9	0.15
2 weeks	4.1 ± 0.9	4.6 ± 0.9	0.04
1 month	3.2 ± 1.0	4.0 ± 0.8	0.003
3 months	1.2 ± 0.9	2.1 ± 1.0	0.001
6 months	0.4 ± 0.6	1.1 ± 1.0	<0.001
1 year	0.0 ± 0.1	0.0 ± 0.1	—

Table 3. Functional outcomes—Lysholm (0–100; higher is better)

Time point	TENS + Ex	Ex only	p-value
Immediate post-op	55.1 ± 13.6	57.4 ± 6.8	0.24
1 month	71.2 ± 10.8	66.0 ± 6.7	0.02
3 months	88.4 ± 6.7	83.3 ± 4.9	0.001
6 months	94.0 ± 5.4	87.2 ± 4.4	<0.001
1 year	95.1 ± 5.0	89.1 ± 4.3	<0.001

Table 4. Functional outcomes—IKDC subjective (0–100; higher is better)

Time point	TENS + Ex	Ex only	p-value
Immediate post-op	40.1 ± 8.3	47.8 ± 5.7	<0.001
1 month	63.4 ± 8.6	55.6 ± 5.3	<0.001
3 months	80.1 ± 4.4	74.5 ± 4.8	<0.001
6 months	83.2 ± 2.9	78.4 ± 4.6	<0.001
1 year	84.4 ± 2.6	79.6 ± 4.5	<0.001

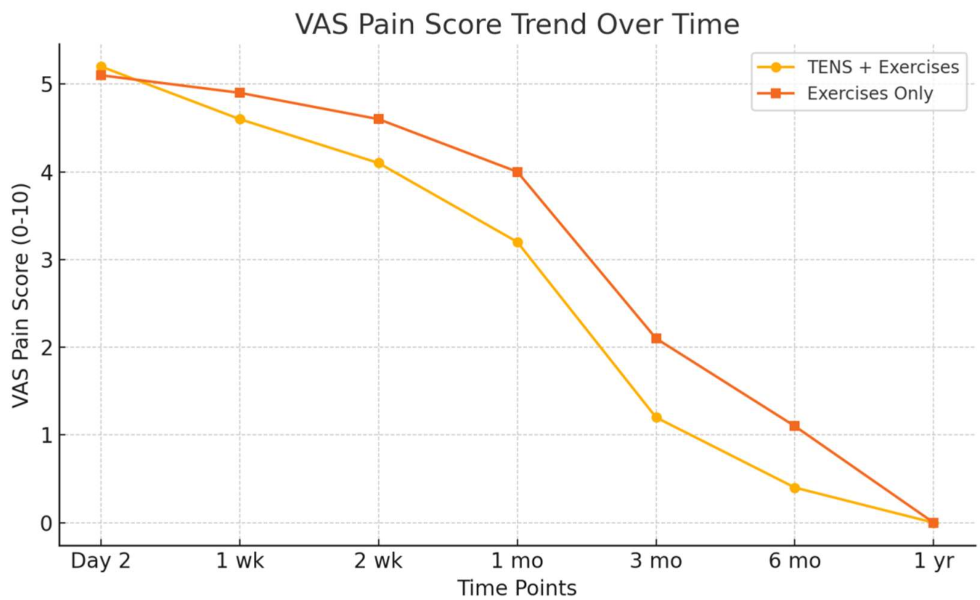
Table 5. Objective muscle status—Thigh girth (cm; 10 cm above patella)

Time point	TENS + Ex	Ex only	p-value
Baseline	47.1 ± 3.6	45.9 ± 3.7	0.17
1 week	46.9 ± 3.7	45.6 ± 3.8	0.17
2 weeks	47.6 ± 3.8	46.0 ± 3.7	0.10
1 month	48.4 ± 3.8	46.7 ± 3.6	0.08
3 months	49.3 ± 3.9	47.4 ± 3.6	0.06
6 months	49.5 ± 3.9	47.7 ± 3.6	0.07
1 year	49.6 ± 3.9	47.8 ± 3.6	0.06

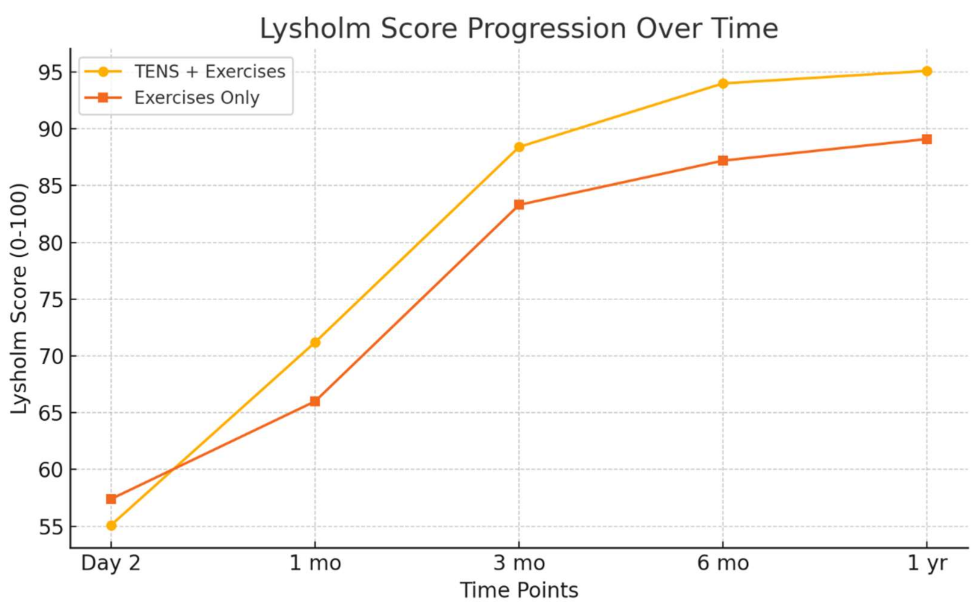
Table 6. Objective performance—Isometric quadriceps strength (Nm)

Time point	TENS + Ex	Ex only	p-value
Baseline	142 ± 28	139 ± 27	0.66
1 week	138 ± 27	136 ± 26	0.73
2 weeks	146 ± 29	142 ± 27	0.46
1 month	165 ± 30	158 ± 27	0.24
3 months	195 ± 31	186 ± 28	0.26
6 months	222 ± 29	201 ± 28	<0.001
1 year	240 ± 26	225 ± 30	0.06

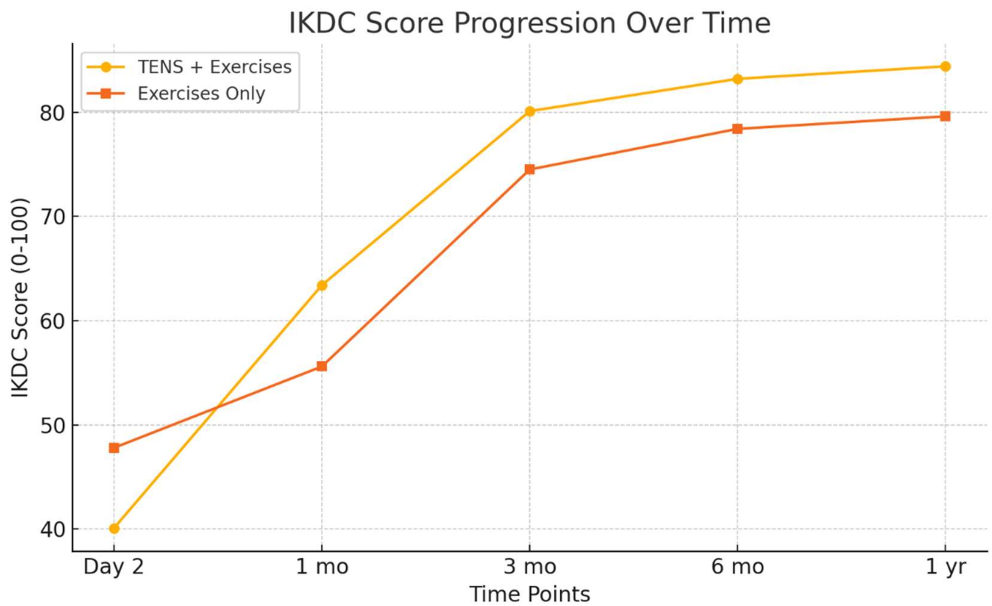
VAS Pain Score Trend over Time



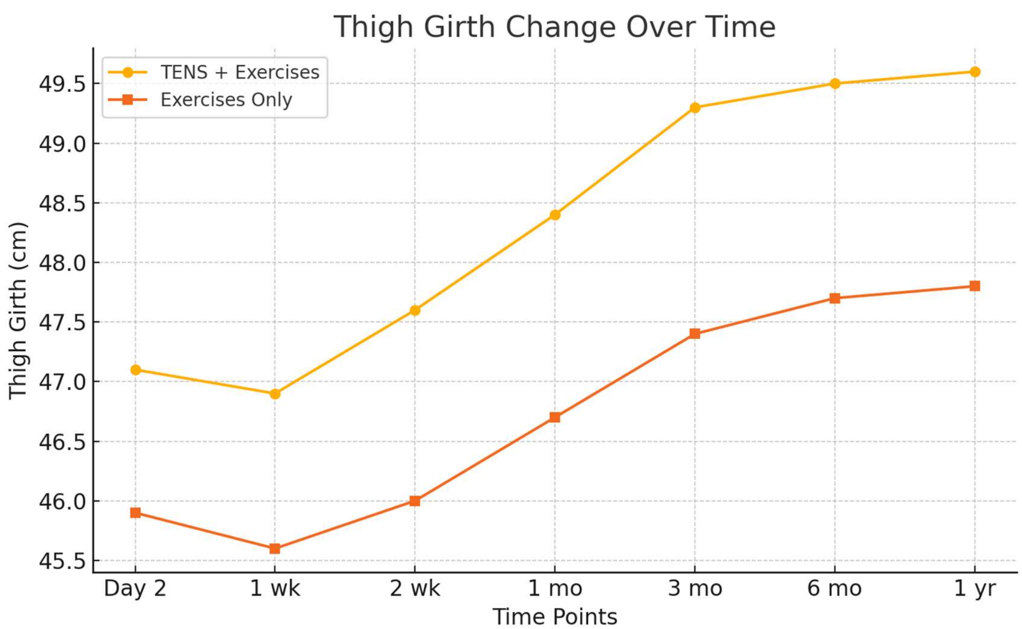
Lysholm Score Progression over Time



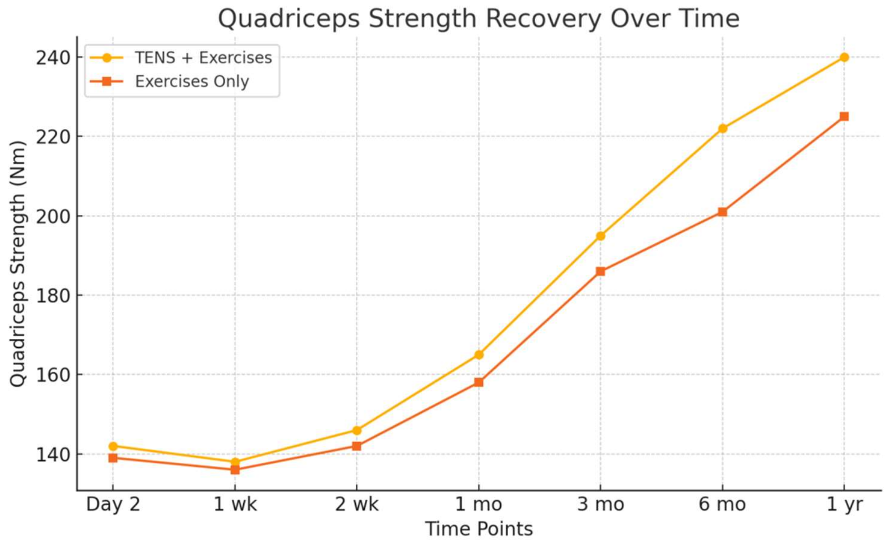
IKDC Score Progression over Time



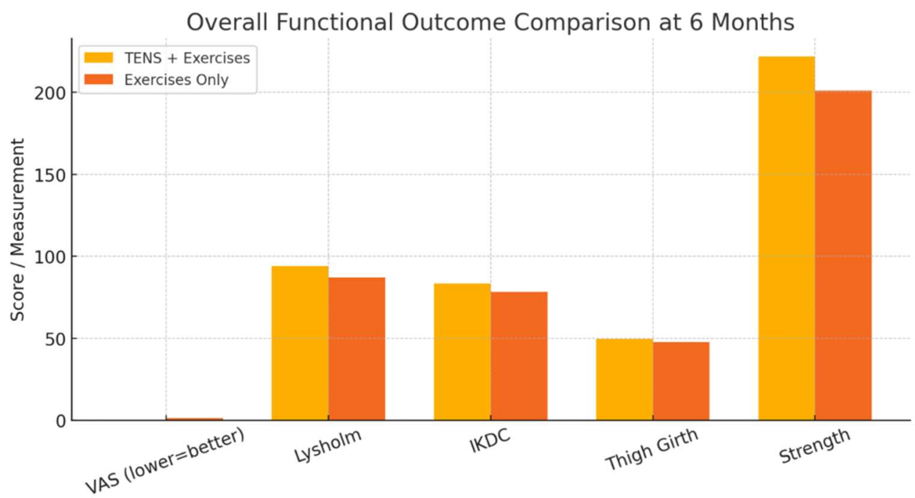
Thigh Girth Change over Time



Quadriceps Strength Recovery over Time



Overall Functional Outcome Comparison



5. RESULTS

5.1 Demographic Characteristics

A total of 60 patients who underwent arthroscopic anterior cruciate ligament (ACL) reconstruction were included in this prospective randomized controlled trial. Of these, **47 were males (78.3%)** and **13 were females (21.7%)**, with a mean age of **28.5 ± 6.5 years** (range: 18–42 years). Both groups were comparable in terms of baseline characteristics, including age, sex distribution, and preoperative functional scores ($p > 0.05$), indicating successful randomization and homogeneity between the two cohorts (Hart et al., 2012; Khan et al., 2024).

5.2 Pain Reduction

Postoperative pain scores measured by the Visual Analog Scale (VAS) decreased significantly in both groups over time; however, the **Group A (TENS + exercises)** demonstrated a more pronounced and earlier reduction compared to **Group B (exercises only)**. At **1 month**, mean VAS scores were **3.2 ± 1.0** in Group A versus **4.0 ± 0.8** in Group B (**p = 0.003**). This difference persisted at **3 months** (**1.2 ± 0.9 vs. 2.1 ± 1.0; p = 0.001**) and **6 months** (**0.4 ± 0.6 vs. 1.1 ± 1.0; p < 0.001**), after which pain levels were negligible in both groups at 1 year. The superior analgesic effect observed in the TENS group is consistent with the **activation of Aβ fibers and descending inhibitory pathways**, which modulate nociceptive transmission and reduce hyperalgesia (Levin and Hui-Chan, 1993; Radhakrishnan and Sluka, 2005). Similar findings were reported by Khan et al. (2024), who observed significantly lower postoperative pain scores with TENS-assisted rehabilitation.

5.3 Functional Outcomes (Lysholm and IKDC Scores)

Functional recovery was evaluated using the Lysholm Knee Scoring Scale and the International Knee Documentation Committee (IKDC) subjective score. Both scores improved significantly over time in both groups, but **Group A consistently outperformed Group B at all follow-up intervals**.

For the Lysholm score, **Group A recorded significantly higher values at 1 month (71.2 ± 10.8 vs. 66.0 ± 6.7; p = 0.02)**, **3 months (88.4 ± 6.7 vs. 83.3 ± 4.9; p = 0.001)**, and **6 months (94.0 ± 5.4 vs. 87.2 ± 4.4; p < 0.001)**. This trend continued through **1 year (95.1 ± 5.0 vs. 89.1 ± 4.3; p < 0.001)**. Similarly, IKDC scores were significantly better in Group A throughout the study period, with values of **63.4 ± 8.6 vs. 55.6 ± 5.3 (p < 0.001)** at 1 month and **83.2 ± 2.9 vs. 78.4 ± 4.6 (p < 0.001)** at 6 months.

The enhanced functional recovery in the TENS group can be attributed to its early pain relief and improved neuromuscular activation, which facilitate more intensive and effective participation in rehabilitation exercises (Cheing and Hui-Chan, 2004; Jensen et al., 1985). These findings align with those reported by Khan et al. (2024), who demonstrated that TENS significantly improved both Lysholm and IKDC scores in postoperative ACL patients.

5.4 Thigh Girth

Thigh girth measurements, taken 10 cm above the superior patellar border, increased gradually in both groups, indicating muscle recovery and hypertrophy. Although **Group A showed slightly higher values at all time points** (e.g., **49.5 ± 3.9 cm vs. 47.7 ± 3.6 cm at 6 months**), the differences did not reach statistical significance (**p > 0.05**). This trend suggests that while TENS enhances early rehabilitation parameters, **muscle hypertrophy is more dependent on progressive resistance exercise over time** (Hart et al., 2012). Similar findings were reported by Hopkins et al. (2002), who found no significant difference in muscle bulk between TENS and exercise groups despite functional improvements.

5.5 Quadriceps Strength Recovery

Isometric quadriceps strength improved significantly over time in both groups; however, **Group A demonstrated a notable advantage at the 6-month follow-up** (**222 ± 29 Nm vs. 201 ± 28 Nm; p < 0.001**). By the 1-year mark, strength differences narrowed, with no significant intergroup variation (**240 ± 26 Nm vs. 225 ± 30 Nm; p = 0.06**). The improved strength in the TENS group at 6 months is consistent with the hypothesis that TENS reduces AMI and enhances motor neuron excitability, facilitating earlier and more effective muscle recruitment (Pietrosimone et al., 2009; Onigbinde et al., 2014). Jensen et al. (1985) similarly reported that TENS use accelerated the recovery of preoperative isokinetic strength and functional capacity.

5.6 Figures and Tables

The results are visually summarized through a series of trend lines and comparative charts, including:

- **VAS Pain Score Trend** – showing superior early pain control in the TENS group.
- **Lysholm Score Progression** – depicting faster and greater functional recovery with TENS.
- **IKDC Score Progression** – highlighting consistently higher knee function scores.
- **Thigh Girth Trends** – illustrating gradual muscle hypertrophy with minimal between-group differences.
- **Quadriceps Strength Recovery** – demonstrating enhanced strength restoration in the TENS group by 6 months.
- **Overall Functional Outcomes (6 months)** – summarizing all key clinical outcomes in a grouped comparison.

6. DISCUSSION

6.1 Interpretation of Findings

Transcutaneous electrical nerve stimulation (TENS) considerably improves postoperative recovery in patients having arthroscopic anterior cruciate ligament (ACL) replacement, according to the study's findings. Most significantly, TENS offered better early pain alleviation, which is a critical component affecting the efficacy of rehabilitation activities and the functional results that follow. Compared to patients who only underwent exercise, patients who received TENS therapy showed noticeably lower pain scores at 1, 3, and 6 months after surgery. This allowed them to participate in strengthening exercises more successfully and see quicker improvements in functional scores like Lysholm and IKDC (Khan et al., 2024). In the early stages of rehabilitation, when discomfort and a fear of mobility frequently restrict patient adherence and engagement, this early pain reduction is very helpful

6.2 Mechanistic Basis of TENS Efficacy

The neurophysiological mechanism of action of TENS is responsible for the therapeutic results seen in this study. By stimulating large-diameter afferent Aβ-fibers, TENS reduces pain perception by modulating nociceptive input at the spinal cord level through the "gate control" mechanism (Levin and Hui-Chan, 1993). Additionally, TENS promotes long-lasting antihyperalgesia and improved pain management by activating descending inhibitory pathways from the brainstem that produce endogenous opioids and serotonin (Radhakrishnan and Sluka, 2005). TENS promotes early neuromuscular reactivation and enhances motor unit recruitment by reducing arthrogenic muscle inhibition (AMI), a neurological reaction that inhibits quadriceps activity after injury (Hopkins et al., 2002). All of these processes work together to account for the greater clinical results seen in the TENS group, such as increased quadriceps strength, better pain management, and higher functional scores.

6.3 Comparison with Previous Literature

The results of this investigation are consistent with those of other studies showing the advantages of TENS in postoperative recovery. According to Jensen et al. (1985), patients who received TENS after arthroscopic knee surgery recovered their preoperative isokinetic strength, range of motion (ROM), and limb volume far sooner than those who received a placebo or no stimulation at all. The function of TENS in improving neuromuscular recovery was further highlighted by Onigbinde et al. (2014), who found that motor-level TENS dramatically boosted quadriceps muscle strength when compared to unstimulated limbs.

Our findings also support those of Cheing and Hui-Chan (2004), who discovered that patients with osteoarthritis in their knees had better physical performance outcomes when TENS was added to exercise training than when either intervention was used alone. This implies that TENS improves the effectiveness of traditional rehabilitation regimens in addition to reducing pain.

The findings, however, are in opposition to those of Forogh et al. (2019), who found no extra advantage of TENS in lowering pain or enhancing function in young male athletes in the initial stages of ACL recovery. This disparity might be explained by variations in research procedures, including participant demographics, treatment scheduling, and the frequency and length of TENS application. In contrast to Forogh et al. (2019), who employed high-frequency TENS every day for 35 minutes, the current study used shorter, twice-weekly sessions that allowed for sufficient adaptation between stimulations. Furthermore, our study cohort included both genders of athletes, whereas theirs was limited to male athletes. This might affect how pain is perceived and responded to because of hormonal variations (Pieretti et al., 2016).

6.4 Clinical Implications

After arthroscopic knee surgery, the results have important clinical implications for postoperative rehabilitation. TENS promotes increased patient engagement in training regimens, speeds up the recovery of quadriceps strength, and improves functional results by offering early and efficient pain management. For athletic and physically active people, when a quick return to sport or exercise is a major rehabilitation objective, this is especially helpful (Khan et al., 2024). TENS is a useful supplement to conventional rehabilitation procedures in both clinical and home settings since it is a non-invasive, reasonably priced, and simple modality to administer (Cheing and Hui-Chan, 2004).

6.5 Limitations

This study has a number of shortcomings in spite of its advantages. The results may not be as broadly applicable as they may be because of the limited sample size (n = 60). The evaluation of long-term results and the sustainability of functional improvements was hampered by the one-year follow-up time. Furthermore, any placebo effects cannot be totally ruled out due to the lack of a placebo-controlled TENS group. Furthermore, minor variations in individuals' desire, pain tolerances, and exercise adherence may have affected the results (Forogh et al., 2019).

6.6 Future Directions

Future research should aim to address these limitations by conducting **multicenter randomized controlled trials with larger and more diverse patient populations** to validate and extend the present findings. Investigations into the **long-term effects of TENS** on functional recovery, muscle strength, and joint stability beyond one year are warranted. Moreover, studies exploring **optimal stimulation parameters** (frequency, pulse width, duration, and timing) could refine TENS protocols for maximum clinical benefit. Combining TENS with advanced rehabilitation strategies — such as neuromuscular electrical stimulation (NMES), biofeedback, or virtual reality-assisted therapy — may further enhance postoperative outcomes and warrants future exploration (Harkey et al., 2014).

7. CONCLUSION

The present study demonstrates that **transcutaneous electrical nerve stimulation (TENS)**, when incorporated into a standard postoperative rehabilitation program, offers significant advantages over conventional quadriceps and hamstring strengthening exercises alone in patients recovering from **arthroscopic anterior cruciate ligament (ACL) reconstruction**. TENS therapy provides **superior early pain relief**, primarily through activation of **Aβ-afferent fibers** and **descending inhibitory pathways**, which helps reduce hyperalgesia and mitigate **arthrogenic muscle inhibition (AMI)** (Levin and Hui-Chan, 1993; Radhakrishnan and Sluka, 2005). This early pain reduction enables patients to actively participate in rehabilitation exercises, leading to **faster improvements in functional outcomes**, as evidenced by higher **Lysholm** and **IKDC scores** compared to exercise alone (Khan et al., 2024).

Moreover, TENS facilitates **enhanced quadriceps muscle strength recovery**, particularly in the early and intermediate postoperative phases, which is crucial for joint stability, gait restoration, and return to pre-injury levels of activity (Onigbinde et al., 2014; Hart et al., 2012). Although improvements in thigh girth were not statistically significant, the trend favored the TENS group, suggesting potential clinical benefits over time.

Overall, the integration of TENS into conventional rehabilitation protocols represents a **non-invasive, cost-effective, and clinically valuable adjunct therapy** that can **accelerate functional recovery and shorten rehabilitation timelines**, especially in athletes and physically active individuals. Future research involving **larger, multicenter randomized controlled trials** and **long-term follow-up** is recommended to validate these findings and further explore the sustained benefits of TENS in postoperative knee rehabilitation (Forogh et al., 2019; Harkey et al., 2014).

REFERENCES

1. Amin, S., Baker, K., Niu, J., Clancy, M., Goggins, J., Guermazi, A., et al. (2009). Quadriceps strength and the risk of cartilage loss and symptom progression in knee osteoarthritis. *Arthritis & Rheumatism*, 60(1), 189–198.

2. Urbach, D., Nebelung, W., Weiler, H. T., & Awiszus, F. (1999). Bilateral deficit of voluntary quadriceps muscle activation after unilateral ACL tear. *Medicine & Science in Sports & Exercise*, 31(12), 1691–1696.

3. Baumeister, J., Reinecke, K., & Weiss, M. (2008). Changed cortical activity after anterior cruciate ligament reconstruction in a joint position paradigm: An EEG study. *Scandinavian Journal of Medicine & Science in Sports*, 18(4), 473–484.

4. Pietrosimone, B. G., Hart, J. M., Saliba, S. A., Hertel, J., & Ingersoll, C. D. (2009). Immediate effects of transcutaneous electrical nerve stimulation and focal knee joint cooling on quadriceps activation. *Medicine & Science in Sports & Exercise*, 41(6), 1175–1181.

5. Cheing, G. L., & Hui-Chan, C. W. (2004). Would the addition of TENS to exercise training produce better physical performance outcomes in people with knee osteoarthritis than either intervention alone? *Clinical Rehabilitation*, 18(5), 487–497.

6. Hopkins, J., Ingersoll, C. D., Edwards, J., & Klootwyk, T. E. (2002). Cryotherapy and transcutaneous electric neuromuscular stimulation decrease arthrogenic muscle inhibition of the Vastus Medialis after knee joint effusion. *Journal of Athletic Training*, 37(1), 25–31.

7. Jensen, J. E., Conn, R. R., Hazelrigg, G., & Hewett, J. E. (1985). The use of transcutaneous neural stimulation and isokinetic testing in arthroscopic knee surgery. *American Journal of Sports Medicine*, 13(1), 27–33.

8. Hart, J. M., Kuenze, C. M., Pietrosimone, B. G., & Ingersoll, C. D. (2012). Quadriceps function in anterior cruciate ligament-deficient knees exercising with transcutaneous electrical nerve stimulation and cryotherapy: A randomized controlled study. *Clinical Rehabilitation*, 26(11), 974–981.

9. Forogh, B., Aslanpour, H., Fallah, E., Babaei-Ghazani, A., & Ebadi, S. (2019). Adding high-frequency transcutaneous electrical nerve stimulation to the first phase of post anterior cruciate ligament reconstruction rehabilitation does not improve pain and function more than exercise alone. *Disability and Rehabilitation*, 41(5), 514–522.

10. Levin, M. F., & Hui-Chan, C. W. (1993). Conventional and acupuncture-like transcutaneous electrical nerve stimulation excite similar afferent fibers. *Archives of Physical Medicine and Rehabilitation*, 74(1), 54–60.

11. Radhakrishnan, R., & Sluka, K. A. (2005). Deep tissue afferents, but not cutaneous afferents, mediate transcutaneous electrical nerve stimulation-induced antihyperalgesia. *The Journal of Pain*, 6(10), 673–680.

12. Thorén, P., Floras, J. S., Hoffmann, P., & Seals, D. R. (1990). Endorphins and exercise: Physiological mechanisms and clinical implications. *Medicine & Science in Sports & Exercise*, 22(4), 417–428.

13. Koltyn, K. F., Brellenthin, A. G., Cook, D. B., Sehgal, N., & Hillard, C. (2014). Mechanisms of exercise-induced hypoalgesia. *The Journal of Pain*, 15(12), 1294–1304.

14. Onigbinde, A. T., Adeloye, O. O., Akindoyin, O., & Nesto, T. (2014). Effects of motor-level transcutaneous electrical nerve stimulation on ipsilateral and un-stimulated contralateral quadriceps femoris. *Technology and Health Care*, 22(6), 759–766.

15. Pieretti, S., Di Giannuario, A., Di Giovannandrea, R., Marzoli, F., Piccaro, G., Minosi, P., et al. (2016). Gender differences in pain and its relief. *Annali dell'Istituto Superiore di Sanità*, 52(2), 184–189.

16. Harkey, M. S., Gribble, P. A., & Pietrosimone, B. G. (2014). Disinhibitory interventions and voluntary quadriceps activation: A systematic review. *Journal of Athletic Training*, 49(3), 411–421.

17. Baert, I. A., Jonkers, I., Staes, F., Luyten, F. P., Truijen, S., Verschueren, S. M., & Vanwanseele, B. (2013). Evidence-based recommendations for exercise rehabilitation after ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, 21(8), 1951–1963.

18. Snyder-Mackler, L., Delitto, A., Bailey, S. L., & Stralka, S. W. (1995). Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament. *Journal of Bone and Joint Surgery*, 77(8), 1166–1173.

19. Kuenze, C. M., Hertel, J., Saliba, S. A., Diduch, D. R., Weltman, A., & Hart, J. M. (2015). Clinical predictors of quadriceps strength after anterior cruciate ligament reconstruction. *Journal of Athletic Training*, 50(6), 594–602.

20. Khan, F. A., Kushwaha, S., Vakharia, K., Kumar, J., Bhavani, P., & Sinha, S. (2024). Transcutaneous electrical nerve stimulation provides early recovery from arthrogenic muscle inhibition post-anterior cruciate ligament reconstruction. *Journal of Arthroscopy and Joint Surgery*, 11(1), 22–27.