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ORIGINAL ARTICLE

# COMPARATIVE EFFECTS OF LOW INTENSITY LASER THERAPY VERSUS MICROWAVE THERAPY ON PAIN AND FUNCTION IN PATIENTS WITH KNEE OSTEOARTHRITIS: A RANDOMIZED CLINICAL TRIAL

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**Priyank Mohan [1], Surya Prakash Sharma[2], Rishan[3], Amresh Kumar[4]**

**Corresponding Author:**
[1]Priyank Mohan, Sr. Physiotherapist, Northern Railway Central Hospital, New Delhi, India,
Mail id: priyankmohan1982@gmail.com

**Co Authors:**
[2]Sr. DMO/Ortho/Northern Railway Central Hospital, New Delhi, India
[3]Rishan, BPT intern, Northern Railway Central Hospital, New Delhi, India
[4]Amresh Kumar, Sr. Physiotherapist/Northern Railway Central Hospital, New Delhi, India

**ABSTRACT**

**Background:** Knee osteoarthritis (OA), a degenerative joint disease characterized by pain, stiffness, and functional decline, significantly impacts quality of life, particularly in aging populations. Non-pharmacological therapies like Low-Level Laser Therapy (LLLT) and Microwave Therapy (MWT) are increasingly explored for their potential to alleviate symptoms without systemic side effects. While LLLT employs photo-biomodulation to reduce inflammation and enhance tissue repair, MWT relies on thermal mechanisms for pain. This study aimed to compare the efficacy of LLLT and MWT in reducing pain and improving functional activity in patients with knee OA grades 2 and 3, using the Numeric Pain Rating Scale (NPRS) and the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC). **Methods:** A randomized controlled trial included 30 participants (15 per group) diagnosed with knee OA (Kellgren-Lawrence grades 2-3). Group A received LLLT (830nm, 32 J/cm²/session) alongside a standardized exercise protocol, while Group B underwent MWT (2450 MHz, 20 minutes/session) with the same exercises. Interventions were administered every alternate day for three weeks. Pain (NPRS) and function (WOMAC) were assessed pre- and post-intervention. Statistical analysis used paired and independent t-tests via SPSS. **Result**: LLLT demonstrated superior outcomes: NPRS scores decreased by 3.47 ± 0.74 ($p < 0.001$) vs. 1.27 ± 0.96 in MWT ($p < 0.05$). WOMAC improvements were 21.47 ± 9.04 (LLLT) vs. 10.40 ± 5.43 (MWT) ($p < 0.001$). These results align with LLLT's anti-inflammatory and mitochondrial-modulating mechanisms, contrasting MWT's transient thermal effects. **Conclusion:** LLLT outperforms MWT in managing pain and function in moderate knee OA, attributed to its bio-modulatory effects on inflammation and tissue repair. While MWT offers short-term relief, LLLT's sustained benefits position it as a better non-pharmacological therapy.

**Keywords:** Low-Level Laser Therapy, Microwave Therapy, Thermal mechanisms

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## INTRODUCTION

Knee osteoarthritis (OA) is a leading cause of disability, particularly among the elderly, characterised by cartilage degradation, synovial inflammation, and joint stiffness. With the global rise in obesity and an aging population, the prevalence of osteoarthritis is expected to grow, placing greater pressure on healthcare systems [1].

For patients with knee OA, an individualised approach combining medication, physical therapy, and lifestyle modifications is ideal. In cases of severe OA with persistent pain and disability, surgical options like knee replacement may be necessary[2,3].

Early OA is typically characterised by mild knee pain, minimal radiographic changes (Kellgren & Lawrence grades 0-2), and either arthroscopic or MRI-detected structural damage. Patients with early OA often report intermittent knee pain, mild swelling after physical activity, crepitus, and stiffness that improves with movement[11].

Gender emerged as a significant variable, with women more likely to report knee pain, a finding consistent with prior research linking sex hormones to OA progression[13]. Additionally, patients experiencing widespread pain in multiple body regions showed a higher likelihood of knee pain, suggesting the involvement of central sensitisation mechanisms that amplify pain perception[14].

General health status and comorbidities also played a role, particularly in individuals without radiographic OA; poor overall health, a history of heart attack, and depression were strongly associated with knee pain, underscoring the interplay between systemic health and localised joint symptoms [11]. Furthermore, the presence of OA in other joints, such as the hip or hand, was linked to increased knee pain, potentially due to referred pain patterns or shared pathophysiological pathways[11].

Notably, morning stiffness was observed across all OA grades, including those without radiographic evidence of OA, indicating that this symptom may serve as an early marker of knee OA development[12]. These findings collectively emphasise the complex interplay of biological, psychological, and systemic factors in shaping knee pain experiences among OA patients.

LLLT exerts therapeutic effects through photo biomodulation, primarily targeting mitochondrial cytochrome c oxidase, which enhances ATP production and modulates reactive oxygen species (ROS). This process reduces oxidative stress, promotes cell proliferation, and stimulates anti-inflammatory pathways.

LLLT also increases nitric oxide (NO) release, improving microcirculation and reducing edema[4,5]. Gene expression changes, such as up-regulation of growth factors (e.g., PDGF-C) and down-regulation of apoptotic markers (e.g., Caspase 6), further support tissue repair[18, 6].

A randomized controlled trial[8] using 850 nm LLLT (48 J/cm²) reported significant reductions in pain (47% at rest, 40% during movement) and improved WOMAC scores compared to placebo.

Soleimanpour et al. demonstrated reduced nocturnal pain and improved knee mobility using dual wavelengths (810 nm and 890 nm),

with effects attributed to enhanced collagen synthesis and vascularisation[22].

LLLT reduces pro-inflammatory cytokines (e.g., IL-1β, TNF-α) and prostaglandins, mitigating synovial inflammation[4,23]. This aligns with findings from Stelian et al. (1992), where LLLT reduced pain severity in OA patients by 29% using red and infrared wavelengths[24]. Prolonged LLLT application (≥11 weeks) yields durable benefits. A 6-month follow-up study[25] noted sustained pain relief and functional improvement, attributed to LLLT's cumulative anti-inflammatory and tissue-repair effects. Similarly, Rayegani et al. (2017) highlighted enhanced quadriceps strength and mobility in OA patients with extended LLLT protocols[26].

Microwave diathermy is a therapeutic modality widely used in physiotherapy and sports medicine to deliver deep tissue heating while minimising skin temperature rise. Microwave diathermy is particularly effective for treating soft tissue injuries, chronic arthritis, and localised inflammation[17].

The heating mechanism primarily involves the absorption of microwave energy by water-rich tissues, where dipolar rotation of water molecules and ionic movement generate heat.

The penetration depth varies with frequency: 2450 MHz penetrates approximately 1.7 cm in muscle and 11.2 cm in fat, while 915 MHz offers deeper penetration (3 cm in muscle and 17.7 cm in fat), resulting in more uniform heating [16].

Beyond thermal effects, microwave therapy may modulate cellular activity, such as activating Na+/K+ ATPase, though evidence for non-thermal effects remains debated[15, 16].

Clinically, microwave diathermy is effective for conditions like knee osteoarthritis and post-traumatic inflammation but less so for deep joints such as the hip due to energy dissipation in subcutaneous fat.

Enhanced outcomes were observed when deep heating was paired with physical exercise. For instance, diathermy combined with muscle strengthening improved functionality and quality of life. Diathermy at low doses (14.5W, 19 minutes) showed short-term benefits in pain and mobility.

**Aim:** To compare the effectiveness of Low-Level Laser Therapy and Microwave Therapy in reducing pain and improving functional activity in patients with knee osteoarthritis grade 2 and 3.

**Objectives**

**Primary Objective:**

1. To compare the effectiveness of Low-Level Laser Therapy and Microwave Therapy in reducing pain using the NPRS scale in patients with knee osteoarthritis grade 2 and 3.

2. To compare the effectiveness of Low-Level Laser Therapy and Microwave Therapy in improving functional activity using the WOMAC scales in patients with knee osteoarthritis grade 2 and 3.

**Secondary Objective:**

1. To assess the individual effect of Low-Level Laser Therapy on pain reduction and functional improvement.
2. To assess the individual effect of Microwave Therapy on pain reduction and functional improvement.
3. To analyse the percentage of pain reduction and functional improvement achieved with each therapy.

4. To determine if Low-Level Laser Therapy provides a statistically and clinically significant advantage over Microwave Therapy in managing knee osteoarthritis.

**MATERIAL AND METHODS**

This study is a randomized controlled trial comparing the effects of Low-Level Laser Therapy (LLLT) and Microwave Therapy (MWT) on pain and functional activity in patients with knee osteoarthritis (OA). Informed and written consent was taken from all patients. A total of 30 participants were recruited and randomly assigned into two groups for three weeks:

• Group A (LLLT Group): Received Low-Level Laser Therapy along with a standard knee osteoarthritis exercise protocol.
• Group B (MWT Group): Received Microwave Therapy along with the same standard knee osteoarthritis exercise protocol.
The proposed study was conducted in the Department of Physiotherapy, Northern Railway Central Hospital, New Delhi.
Duration of Study is 6 Months

**Inclusion Criteria:**
1. Patients diagnosed with knee osteoarthritis (OA) grade 2 or 3 based on the Kellgren-Lawrence classification.
2. Age range: 30–80 years.
3. Both male and female patients.
4. Presence of knee pain for at least 2 months.
5. Willingness to participate and provide informed consent.
6. Ability to perform the prescribed standard exercise protocol.

**Exclusion Criteria:**
1. Patients with knee OA grade 1 or grade 4.
2. History of knee surgery or joint replacement.
3. Presence of inflammatory arthritis (e.g., rheumatoid arthritis, gout).
4. Any recent trauma or injury to the knee within the last 6 months.
5. Use of corticosteroid injections or other intra-articular treatments within the past 3 months.
6. Presence of neurological disorders affecting lower limb function.
7. Patients with pacemakers, metal implants, or other contraindications for microwave therapy.
8. Patients with open wounds, infections, or skin conditions at the treatment site.
9. Pregnant or lactating women.
10. Participation in other clinical trials or physiotherapy interventions for knee OA during the study period.

**Outcome measures** included pain intensity assessed using the Numeric Pain Rating Scale (NPRS) and functional activity measured using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scale.

**History:**
Each participant underwent a detailed history-taking session to record the following:
• Duration and progression of knee pain.
• Past medical history, including any previous knee injuries, surgeries, or other joint disorders.
• Medication history, including the use of analgesics, anti-inflammatory drugs, or corticosteroid injections.
• Functional limitations related to knee pain, such as difficulty in walking, climbing stairs, or performing daily activities.
• Previous physiotherapy or other treatment interventions received for knee OA.

**Investigations:** To confirm the diagnosis and severity of knee osteoarthritis, the following investigations were reviewed:

• Radiographic Assessment (X-ray of the knee joint): Used to classify OA severity based on the Kellgren-Lawrence grading system.

• Baseline NPRS Score: Recorded to assess pain intensity before intervention.

• Baseline WOMAC Score: Assessed to evaluate functional disability before treatment.

• General Physical Examination: Conducted to rule out contraindications to the therapies being used.

**Randomisation:** Participants were randomly assigned into two groups using a computer-generated randomisation method to ensure unbiased allocation. Randomisation was performed by an independent researcher who was not involved in the treatment process.

To minimise bias, the following strategies were employed:

• Single-blinded design: The outcome assessor was blinded to the treatment groups.

• Standardised treatment protocol: Both groups followed the same exercise protocol to ensure uniformity in intervention, with the only difference being the modality used (LLLT vs. MWT).

**Treatment Protocol:** Intervention Duration and Frequency

• The study duration was 3 weeks, with treatment sessions conducted every alternate day for both groups, resulting in a total of 9–11 sessions per patient.• In addition to the therapy sessions, both groups followed a standardised exercise protocol for knee osteoarthritis, performed daily throughout the study period.

**Group 1: Low-Level Laser Therapy (LLLT) Group**

- Patients in this group received Low-Level Laser Therapy (LLLT) with wavelength of 830nm and power of 666mWapplied to the affected knee joint. (BTL 4825s, India).
- The treatment was administered and eight points were irradiated with LLLT; three on the medial side of the knee, three on the lateral side of the knee, and two on the medial edge of the tendon of the biceps femoris muscle and semitendinosus muscle in the popliteal fossa.
- Each point received energy of 4 J/cm$^2$, with a total dose of 32 J/cm$^2$ in each session anatomical points around the knee joint to target pain relief and improve joint function.

**Group 2: Microwave Therapy (MWT) Group**

- Patients in this group received Microwave Therapy (MWT) applied to the affected knee joint.
- The microwave therapy modality was operated at the frequency of 2450MHZ for the duration of 20 minutes. (Thermatur m250+, Germany).
- The therapy aimed to provide deep heating effects to improve circulation, reduce stiffness, and relieve pain.

**Exercise Protocol for Both Groups:**

• In addition to their respective treatment interventions, all patients performed a standardized knee osteoarthritis exercise protocol daily.

• The exercise program included:

1. Quadriceps strengthening exercises (e.g., straight leg raises, isometric contractions)

2. Hamstring strengthening exercises and calf stretches

3. Range of motion exercises (e.g., knee flexion and extension)

• Patients were instructed to perform the exercises at home, with adherence monitored through a logbook or periodic follow-ups.

**Sample Size Calculation:** The sample size was calculated based on a power analysis using the G*Power 3.1 software. A two-tailed t-test was selected to compare the mean difference in outcome scores between two

Independent groups (LLLT and MWT). Based on previous literature and expected effect sizes, the following assumptions were used:

- Effect size (Cohen's d) = 1.0
- Alpha level (Type I error probability) = 0.05
- Power (1 - β) = 0.80

Using these parameters, the required sample size was estimated to be 15 participants per group, resulting in a total of 30 patients. This sample size was sufficient to detect a clinically meaningful difference between the two intervention groups using parametric testing.

**Statistical Methods:** All statistical analyses were performed using IBM SPSS Statistics (version 30.0). Descriptive statistics including mean, standard deviation, minimum, and maximum values were computed for each variable. The Shapiro-Wilk test was used to assess the normality of change scores for NPRS and WOMAC. Within-group comparisons of pre- and post-treatment scores were analyzed using the Paired Samples t-test. To compare the treatment effects between the LLLT and MWT groups, an Independent Samples t-test was applied to the change scores. Effect sizes (Cohen's d, Hedges' g) were calculated to estimate the magnitude of differences. A significance level of $p < 0.05$ was considered statistically significant.

**RESULTS AND OBSERVATIONS**

The patients after proper assessment and diagnosis were checked to fulfill the inclusion criteria of the research. Patients were then randomly divided into two groups A and B via computer generated randomization method. The patients in group A underwent with the treatment using Low Level Laser Therapy (LLLT) and those in group B underwent with treatment using Microwave Therapy (MWT). Both groups of patients were given a standard exercise protocol to be followed. The study duration was 3 weeks, with treatment sessions conducted every alternate day for both groups. The data collected from both groups were statistically analysed using IBM SPSS software (ver. 30.0). Change scores for pain and functional activity were calculated by subtracting post-treatment values from pre-treatment values. Descriptive statistics were used to summarise the data, and appropriate statistical tests were applied based on the distribution of the data. Paired t-tests were used for within-group comparisons, while independent t-tests were used to compare the effectiveness of Low-Level Laser Therapy (LLLT) and Microwave Therapy (MWT). The following were the results of these analyses:

**1. Descriptive Statistics:**

A total of 30 patients participated in the study, with 15 in each group (LLLT and MWT). The

descriptive statistics for the outcome measures are presented below:

- The mean baseline NPRS was 6.47 ± 1.25, and the mean post-treatment score was 4.10 ± 1.61.
- The mean baseline WOMAC score was 56.60 ± 12.36 and the post-treatment score was 40.67 ± 14.17.
- The mean reduction in NPRS was 2.37 ± 1.40, while the mean improvement in WOMAC was 15.93 ± 9.24.

**2. Normality Testing**:

The Shapiro-Wilk test was performed to assess the normality of the change scores for NPRS and WOMAC.

- NPRS Change Score: *p = 0.026*
- WOMAC Change Score: *p = 0.026*

As the p-values were < 0.05, the data are not normally distributed. However, due to the sample size (n=30) and the robustness of parametric tests, paired and independent t-tests were still applied.

**3. Within-Group Comparisons (Paired t-tests):**

LLLT Group:
NPRS decreased from 6.47 ± 1.19 to 3.00 ± 1.00, *t (14) = 7.01, p < 0.001*
WOMAC improved from 60.40 ± 8.42 to 38.93 ± 14.27, *t (14) = 8.78, p < 0.001*
MWT Group: NPRS decreased from 6.47 ± 1.36 to 5.20 ± 1.32, *t (14) = 1.80, p < 0.05*,
WOMAC improved from 52.80 ± 14.64 to 42.40 ± 14.34, *t (14) = 5.10, p < 0.001*

These results show that both groups had significant within-group improvements, but the LLLT group showed a larger effect.

**Group Statistics**

| | Group (LLLT/MWT) | N | Mean | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|---|
| NPRS Change | LLLT | 15 | 3.47 | .743 | .192 |
| | MWT | 15 | 1.27 | .961 | .248 |
| Womac Change | LLLT | 15 | 21.47 | 9.039 | 2.334 |
| | MWT | 15 | 10.40 | 5.435 | 1.403 |

Table 1: Group Statistics

**Independent Samples Test**

| | | Levene's Test for Equality of Variances | | t-test for Equality of Means | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Significance | | Mean | Std. Error | 95% Confidence Interval of the Difference | |
| | | F | Sig. | t | df | One-Sided p | Two-Sided p | Difference | Difference | Lower | Upper |
| NPRS Change | Equal variances assumed | .531 | .472 | 7.013 | 28 | <.001 | <.001 | 2.200 | .314 | 1.557 | 2.843 |
| | Equal variances not assumed | | | 7.013 | 26.333 | <.001 | <.001 | 2.200 | .314 | 1.556 | 2.844 |
| Womac Change | Equal variances assumed | 8.778 | .006 | 4.064 | 28 | <.001 | <.001 | 11.067 | 2.723 | 5.488 | 16.645 |
| | Equal variances not assumed | | | 4.064 | 22.954 | <.001 | <.001 | 11.067 | 2.723 | 5.433 | 16.701 |

**Table 2:** Independent Sample test

**Independent Samples Effect Sizes**

| | | Standardizer[a] | Point Estimate | 95% Confidence Interval Lower | Upper |
|---|---|---|---|---|---|
| NPRS Change | Cohen's d | .859 | 2.561 | 1.570 | 3.527 |
| | Hedges' correction | .883 | 2.491 | 1.527 | 3.431 |
| | Glass's delta | .961 | 2.289 | 1.169 | 3.375 |
| Womac Change | Cohen's d | 7.458 | 1.484 | .660 | 2.287 |
| | Hedges' correction | 7.665 | 1.444 | .642 | 2.225 |
| | Glass's delta | 5.435 | 2.036 | .985 | 3.053 |

a. The denominator used in estimating the effect sizes.
Cohen's d uses the pooled standard deviation.
Hedges' correction uses the pooled standard deviation, plus a correction factor.
Glass's delta uses the sample standard deviation of the control (i.e., the second) group.

**Table 3:** Independent Sample effect size

## DISCUSSION

The present study aimed to compare the efficacy of Low-Level Laser Therapy (LLLT) and Microwave Therapy (MWT) in reducing pain and improving functional activity in patients with knee osteoarthritis (KOA) grades 2 and 3. Over a three-week intervention period, both therapies demonstrated significant within-group improvements in pain (NPRS) and functional outcomes (WOMAC). However, LLLT exhibited superior results compared to MWT, with greater reductions in pain intensity (mean NPRS change: 3.47 vs. 1.27) and functional disability (mean WOMAC change: 21.47 vs. 10.40). These findings align with existing literature on the therapeutic potential of LLLT in OA management while reinforcing the role of MWT as a viable adjunct therapy.

The superior efficacy of LLLT over MWT observed in this trial corroborates prior studies emphasizing photo biomodulation as a potent mechanism for OA symptom relief. For instance, Alghadir et al. (2014) reported a 47% reduction in resting pain with 850 nm LLLT, attributed to anti-inflammatory and mitochondrial-modulating effects. Similarly, Alfredo et al. (2012) demonstrated sustained functional improvements (WOMAC) when combining LLLT with exercise, mirroring the improvement in the current study. The analgesic and regenerative properties of LLLT, mediated through enhanced ATP synthesis, nitric oxide release, and cytokine modulation [19,21], likely contributed to its pronounced benefits.

In contrast, MWT showed moderate efficacy, consistent with Giombini et al. (2011), who reported sustained WOMAC improvements (−32.4 points) at 16 weeks using 433.92 MHz microwaves. However, the shorter duration (3 weeks) and lower frequency (2450 MHz) in the current study may explain the smaller effect size. Microwave therapy's thermal mechanisms-vasodilation, increased collagen extensibility, and nociceptive compound clearance[5, 17], provide transient relief but may lack the cumulative anti-inflammatory benefits of LLLT.

Notably, the combination of both therapies with standardized exercise likely amplified outcomes. Exercise protocols, including quadriceps strengthening and range-of-motion

exercises, are well-established for improving joint stability and function in OA[18, 19]. Synergistic effects between exercise and LLLT have been documented by[6], who attributed sustained pain relief to enhanced tissue repair and reduced inflammation. While MWT also benefits from exercise synergy[28], its reliance on thermal effects may limit long-term efficacy compared to LLLT's cellular-level actions.

The non-thermal, biomodulatory effects of LLLT may also confer advantages in patients with central sensitization or comorbidities like depression, which exacerbate OA pain[11]. By modulating neural pathways and reducing peripheral sensitization, LLLT addresses both nociceptive and neuropathic pain components, whereas MWT's thermal focus may only target the former.

The findings advocate for LLLT as a first-line adjunct therapy for moderate knee OA, particularly in patients seeking non-pharmacological options. Its non-invasive nature, minimal side effects, and compatibility with exercise make it suitable for elderly populations or those with contraindications to

NSAIDs or surgery. However, MWT remains a valuable tool for immediate pain relief, especially in resource-limited settings where laser equipment is unavailable.

Clinicians should consider treatment duration and frequency when prescribing these modalities. While LLLT protocols in this study (10–11 sessions over 3 weeks) yielded significant results, extended regimens (e.g., ≥12 weeks) may enhance durability, as shown by Rayegani et al. (2017)[26]. Similarly, combining MWT with pulsed protocols or lower frequencies (915 MHz) could improve penetration and efficacy.

Patient-specific factors, such as OA severity, comorbidities, and pain etiology, should guide modality selection. For instance, LLLT may benefit patients with inflammatory markers or poor response to analgesics, while MWT could be prioritized for those with muscle stiffness or acute flare-ups.

This study's strengths include a randomized controlled design, blinded outcome assessment, and adherence to standardized protocols, minimizing bias. The use of validated tools (NPRS, WOMAC) enhances reliability, and the inclusion of grades 2-3 OA ensures clinical relevance to moderate cases.

**Limitations and Future suggestions:** Several limitations warrant consideration. First, the small sample size (n=30) limits statistical power and generalizability. Larger trials are needed to validate these findings across diverse populations.

Second, the short intervention (3 weeks) and lack of long-term follow-up preclude conclusions about sustained efficacy. Third, the concurrent exercise protocol, while pragmatic, complicates isolation of the therapies' independent effects. Future studies could incorporate a third group receiving exercise alone to delineate additive benefits.

Additionally, the use of 2450 MHz microwaves may have restricted therapeutic depth compared to lower frequencies. Variability in individual responses to heating versus photobiomodulation also remains unexplored.

Future research should prioritize longitudinal studies to evaluate long-term outcomes and cost-effectiveness of LLLT versus MWT. Exploring combined therapies (e.g., LLLT + MWT) could uncover synergistic effects, particularly for refractory cases. Mechanistic

studies using biomarkers (e.g., IL-1β, COMP) may elucidate pathways underlying LLLT's anti-inflammatory actions.

Dose-response studies are needed to optimize LLLT parameters (wavelength, energy density) for different OA grades. Similarly, investigating MWT at 915 MHz with extended protocols could enhance its utility. Lastly, integrating patient-reported outcomes and qualitative data would provide holistic insights into therapy acceptability and quality-of-life impacts.

These findings advocate for personalized, multimodal approaches tailored to patient needs and OA pathophysiology. Future research must address this study's limitations to refine clinical guidelines and optimize therapeutic outcomes.

## CONCLUSION

This study conclusively demonstrates that Low-Level Laser Therapy (LLLT) is more effective than Microwave Therapy (MWT) in alleviating pain and enhancing functional activity in patients with knee osteoarthritis (OA) grades 2 and 3. The LLLT group exhibited a marked reduction in pain (mean NPRS change: 3.47 vs. 1.27 in MWT; $p < 0.001$) and improved functional outcomes (mean WOMAC improvement: 21.47 vs. 10.40; $p < 0.001$), underscoring its superiority. These results align with LLLT's mechanism of photo bio-modulation, which enhances mitochondrial ATP synthesis, reduces pro-inflammatory cytokines (e.g., IL-1β, TNF-α), and promotes tissue repair. In contrast, MWT's transient thermal effects-primarily vasodilation and nociceptive compound clearance, offer short-term symptomatic relief but fail to address OA's degenerative pathology comprehensively [25-27].

Despite these findings, limitations such as the small sample size (n = 30), short intervention duration (3 weeks), and concurrent use of standardized exercise protocols necessitate cautious interpretation. Future studies should prioritize larger cohorts, extended follow-up periods, and isolated modality assessments to delineate independent therapeutic effects[28]. Additionally, exploring lower MWT frequencies (e.g., 915 MHz) for deeper joint penetration[16] or combined LLLT+MWT protocols may optimize outcomes. Mechanistic research into biomarkers (e.g., COMP, IL-1β) could further validate LLLT's anti-inflammatory claims[29,30].

Clinically, LLLT emerges as a cornerstone therapy for moderate knee OA, particularly for patients seeking non-pharmacological, long-term solutions. MWT retains utility in acute pain management or resource-constrained settings. Integrating these modalities with exercise, as endorsed by ESCEO and OARSI guidelines[21-24], ensures holistic OA care. This study reinforces the imperative for personalized, evidence-based approaches in managing knee OA, bridging gaps between research and clinical practice.

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