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光生物調節療法對全膝關節置換術腫脹改善和恢復促進的影響

The Impact of Photobiomodulation Therapy on Swelling Reduction and Recovery Enhancement in Total Knee Arthroplasty

謝向傑

Hsiang-Chieh Hsieh

指導教授：趙福杉 博士

Advisor: Fu-Shan Jaw, Ph.D.

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國立臺灣大學博士學位論文
口試委員會審定書
PhD DISSERTATION ACCEPTANCE CERTIFICATE
NATIONAL TAIWAN UNIVERSITY

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本論文係謝向傑 D08528020 在國立臺灣大學醫學院暨工學院醫學工程學系完成之博士學位論文，於民國 113 年 12 月 3 日承下列考試委員審查通過及口試及格，特此證明。

The undersigned, appointed by the Department of Biomedical Engineering, National Taiwan University on 8th December, 2024 have examined a PhD dissertation entitled above presented by Hsiang-Chieh, Hsieh D08528020 candidate and hereby certify that it is worthy of acceptance.

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（指導教授 Advisor）

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摘要

腫脹是創傷後損傷和手術後常見的問題，對患者的治療效果和康復有顯著影響。本論文探討了在下肢骨折和全膝關節置換術兩種臨床狀況中，評估和處理腫脹的創新方法。

本研究主要有兩個部分，第一部分研究了生物阻抗分析作為評估急性踝關節骨折後腫脹的非侵入性工具的應用。腫脹由急性發炎和微血管通透性上升引起，會延遲手術時機並增加併發症風險。在 19 名急性踝關節骨折患者中，使用多頻率生物阻抗分析（5–200 kHz）和周徑測量，每 12 小時進行一次測量，直到手術為止。結果顯示，阻抗值與周徑變化之間具有顯著相關性（$r = 0.736$），且患肢與健側肢阻抗比值的下降反映了腫脹的惡化。併發症患者的術前阻抗比值較低（0.69 比 0.82），表明生物阻抗分析是監測軟組織健康的可靠且量化的工具。

第二部分評估了光生物調節療法在減少術後腫脹及改善全膝關節置換患者康復中的作用。在一項隨機對照試驗中，光生物調節療法組每天接受波長為 650 nm 和 850 nm 的光療，同時接受標準術後復健。使用生物阻抗分析評估腫脹，並通過 2 分鐘步行測試、疼痛視覺類比量表和膝關節主動活動範圍測量功能結果。在術後第 6 天，光生物調節療法組的阻抗比值和 2 分鐘步行測試距離（27 公尺比 16 公尺，$p = 0.009$）顯著改善，表明腫脹減輕和行動能力提高。

本研究證實了生物阻抗分析和光生物調節療法作為監測下肢骨折和全膝關節置換術後腫脹的先進工具的潛力。生物阻抗分析能提供精確的腫脹評估，而光生物調節療法能減少水腫並加速康復。這些結果支持將此類技術整合到臨床實踐中以改善患者治療效果，並建議進一步進行大規模研究以驗證其效果。

關鍵詞：生物阻抗分析、光生物調節療法、腫脹處置、全膝關節置換術

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Abstract

Swelling, a critical concern following post-traumatic injuries and surgical procedures, significantly impacts patient outcomes and recovery strategies. This dissertation explores innovative approaches to evaluate and manage swelling in two clinical contexts: lower leg fractures and total knee arthroplasty (TKA).

The first part investigates the use of bioimpedance analysis (BIA) as a non-invasive tool for assessing post-traumatic swelling in 19 patients with acute ankle fractures. Swelling, driven by inflammatory and microvascular responses, delays surgical intervention and increases complications. Multifrequency BIA (5–200 kHz) and circumferential measurements were performed at 12-hour intervals prior to surgery. Results revealed a strong correlation (r = 0.736) between impedance and circumferential changes, with declining impedance ratios reflecting worsening swelling. Complications were associated with lower preoperative impedance ratios (0.69 vs. 0.82), highlighting BIA as a reliable, quantifiable method for monitoring soft tissue health.

The second part evaluates photobiomodulation therapy (PBMT) in reducing postoperative swelling and enhancing recovery in 30 TKA patients. In a randomized controlled trial, the PBMT group received daily light therapy (650 nm and 850 nm wavelengths) alongside standard care. Swelling was assessed using BIA, while

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functional outcomes were measured through the 2-minute walk test (2MWT), visual analog scale (VAS) for pain, and active range of motion (aROM). PBMT significantly improved impedance ratios and 2MWT distances (27 m vs. 16 m, $p = 0.009$) by postoperative day 6, indicating reduced swelling and enhanced mobility.

This research demonstrates the potential of BIA and PBMT as advanced tools for managing swelling in lower leg fractures and TKA. BIA provides precise swelling assessment, while PBMT reduces edema and accelerates recovery. These findings support integrating these technologies into clinical practice to improve patient outcomes, warranting further large-scale studies for validation.

Keywords: bioimpedance analysis, photobiomodulation therapy, low-level laser therapy, swelling management, total knee arthroplasty

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Chapter 1. Introduction to Post-Traumatic and Post-Surgery Swelling

Swelling, or edema, is a common physiological response following trauma and surgical interventions, particularly in the lower extremities. In fractures, swelling arises due to inflammatory and microvascular changes triggered by tissue injury. This response, while integral to the healing process, can result in localized hypoxia, increased compartment pressure, and secondary complications such as blister formation, muscle necrosis, or even compartment syndrome.

Post-surgical swelling, on the other hand, is driven by inflammatory responses to soft tissue manipulation, hardware implantation, and surgical trauma. This swelling can impair rehabilitation, delay weight-bearing activities, and hinder functional recovery. Persistent postoperative edema may lead to wound dehiscence, infection, and chronic stiffness, impacting the overall clinical outcome and patient quality of life. Addressing swelling effectively is essential for reducing complications, improving recovery timelines, and enhancing surgical outcomes.

Swelling is a prevalent and significant concern in orthopedic cases, such as lower leg fractures and total knee arthroplasty. It can impede patient recovery and rehabilitation, leading to increased healthcare costs and a higher risk of clinical complications. Therefore, a comprehensive understanding, accurate evaluation, and

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effective management of swelling are essential to enhance patient outcomes and optimize treatment success.

Swelling after lower leg fracture

Lower leg fractures represent a significant clinical issue, with an annual incidence of approximately 40,000 cases in Taiwan. Effective management of these closed fractures requires careful assessment of soft tissue, which plays a critical role in treatment outcomes. Following blunt trauma, the soft tissue response involves microvascular changes and inflammatory processes that lead to localized tissue hypoxia and acidosis, contributing to an elevation in compartment pressure(1). This increase in pressure heightens the risk of complications, including blister formation, muscle necrosis, and, in severe cases, compartment syndrome. Consequently, surgery is often delayed for 7-14 days to allow for swelling to subside, a delay that may alleviate complication rates but also extends patient discomfort and increases healthcare costs(2). Determining the appropriate timing for surgery post-swelling reduction is therefore essential to balance complication rates with healthcare resource utilization.

Swelling After Total Knee Arthroplasty

Total knee arthroplasty (TKA) is a highly effective surgical intervention for managing severe osteoarthritis, offering significant pain relief and improved joint function for patients suffering from advanced degenerative knee conditions. While

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TKA generally yields excellent long-term outcomes, the immediate postoperative period often involves significant discomfort and complications, particularly swelling.

Postoperative swelling is a frequent issue that can adversely impact early rehabilitation and recovery. Swelling following TKA results from the body's natural inflammatory response to surgical trauma. The invasive nature of TKA, involving extensive soft tissue manipulation, bone cutting, and the placement of prosthetic components, often triggers an acute inflammatory reaction. This process leads to fluid accumulation in and around the knee joint and surrounding tissues. This swelling is associated with reduced knee extension strength(3, 4), impaired mobility, lower patient satisfaction(5), and extended recovery periods(6).

Swelling peaks within the first few days after surgery and may persist for weeks or even months in some patients, contributing to stiffness, pain, and reduced range of motion. In severe cases, prolonged swelling can delay rehabilitation progress, impair wound healing, and increase the risk of complications such as infection or venous thromboembolism.

Despite the expected nature of swelling, approximately 20% of patients report substantial and prolonged edema, even with current postoperative care protocols(7). This highlights the need for effective strategies to minimize swelling and its associated functional impairments.

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Time course of swelling resolution

The time course of swelling resolution has not been comprehensively studied in previous research. One animal study demonstrated that intramuscular pressure peaks at 24 hours post-injury and then gradually decreases over 120 hours(8). This study also found that during the swelling phase, functional capillary density decreases, macromolecular leakage increases, and leukocyte-endothelial interactions intensify, indicating an inflammatory process. However, it remains unclear whether these findings translate directly to post-traumatic conditions in clinical settings.

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Chapter 2. Evaluation and Monitoring of Swelling

In clinical practice, swelling reduction is primarily assessed through physical examination techniques, such as observing blister resolution and the wrinkle skin test. Although some objective methods, like circumferential measurement with tape or water displacement(9), are available, they can cause patient discomfort and may lack precision due to variability in technique. Advanced imaging modalities, including ultrasound, CT, and MRI, offer more accurate assessments but are costly and unsuitable for repeated monitoring(10). Therefore, identifying a measurement approach that is non-invasive, rapid, affordable, reliable, quantifiable, and feasible for sequential monitoring is essential.

Bioimpedance analysis (BIA)

Bioimpedance is a measurement principle based on the body's opposition to an alternating electrical current, providing valuable insights into tissue composition and physiological changes (Fig.1). This opposition, known as impedance, is determined by two key components: resistance and reactance. Resistance represents the opposition to current flow within the conductive body fluids and tissues, while reactance arises from the capacitive properties of cell membranes, which temporarily store and release energy as the current passes. Together, these components influence the phase angle (PA),

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which is the shift in phase between the voltage and current waveforms as they traverse the tissue (Fig. 2). The phase angle is considered a useful indicator of cellular health and integrity, as it reflects the balance between resistance and reactance(11). In clinical settings, bioimpedance analysis is utilized to assess parameters like fluid balance, tissue health, and body composition, making it a valuable tool in medical diagnostics and monitoring.

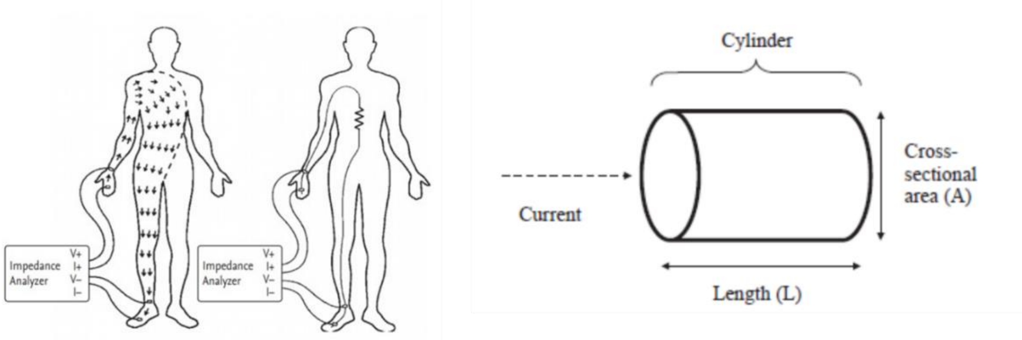

Fig1. The principle of bioelectrical impedance analysis (BIA) relies on electrical currents traveling through a body segment, modeled as a cylindrical component, allowing for impedance measurement. Nephrourol Mon. 2017 January; 9(1):e41514

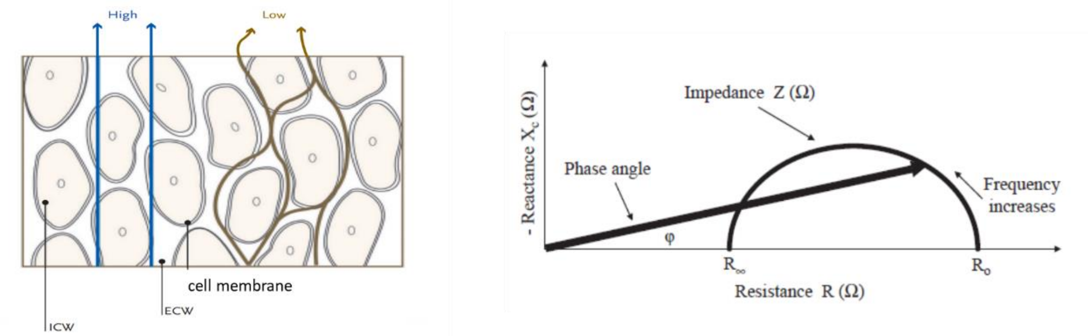

Fig2. Illustration of electric current flow through cellular and intercellular spaces, contributing to reactance and resistance; the phase angle is derived from these two variables.
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Clinical Applications of BIA

1. General Health Evaluation

In general health evaluation, BIA is extensively used to assess body composition, including fat mass, lean body mass, and total body water (TBW). These measurements are essential for evaluating nutritional status, guiding weight management, and monitoring physical fitness. Clinically, BIA is applied in managing obesity, where body composition changes provide more accurate information than weight alone in evaluating the efficacy of interventions like diet or exercise programs(11). Similarly, BIA is used in sports medicine to optimize athlete performance by tracking muscle mass and hydration levels.

In chronic diseases such as diabetes, cardiovascular disease, and chronic kidney disease (CKD), BIA plays a critical role in monitoring disease progression. For instance, in CKD patients undergoing hemodialysis, BIA helps identify fluid overload and guides fluid removal during dialysis sessions, reducing the risk of complications such as hypertension and cardiac overload(12). Additionally, the phase angle derived from BIA—a parameter reflecting cellular integrity and health—is gaining recognition as a prognostic marker in cancer, critical illness, and aging populations(13). Its application in such diverse conditions underscores BIA's value in general health management and risk stratification.

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2. Lymphedema Evaluation

BIA is increasingly used in the evaluation and management of lymphedema, a chronic condition characterized by localized fluid accumulation due to lymphatic dysfunction. Traditional methods for lymphedema assessment, such as limb circumference measurements or water displacement, are often imprecise and may fail to detect early-stage fluid changes. BIA offers a sensitive and objective alternative by measuring extracellular fluid (ECF), a key component in lymphedema.

Lymphedema most commonly occurs after cancer treatments, such as lymph node dissection or radiation therapy, with breast cancer survivors being particularly at risk. Studies have demonstrated that BIA can detect subclinical lymphedema before it becomes clinically apparent, enabling early intervention and better outcomes(13).

Beyond detection, BIA also aids in monitoring treatment efficacy, such as the reduction of ECF following interventions like manual lymphatic drainage, compression therapy, or decongestive therapy. Its ability to provide precise, reproducible data makes it invaluable in both clinical practice and research, where standardized and reliable monitoring tools are critical for assessing therapeutic outcomes.

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3. Swelling After Trauma

Swelling or edema is a hallmark response to trauma, driven by inflammation, vascular permeability changes, and fluid accumulation in injured tissues. The management of post-traumatic swelling is crucial for reducing complications, optimizing rehabilitation, and improving patient outcomes. Traditional methods for assessing swelling, such as visual inspection, limb circumference measurements, or imaging, have limitations in sensitivity and reproducibility. BIA provides a more objective and quantitative approach by distinguishing between intra- and extracellular fluid compartments.

In acute trauma settings, such as lower leg fractures, BIA has been shown to correlate well with traditional measurements like limb circumference while offering additional insights into tissue health and cellular integrity(14). For instance, tracking bioimpedance changes may allow clinicians to monitor the resolution of swelling over time, helping to determine the appropriate timing for surgical intervention. Moreover, the phase angle and reactance components of BIA provide information about cellular damage, which can aid in evaluating tissue recovery.

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Chapter 3. Clinical Trial of BIA for Post-Traumatic Swelling of Patients with Ankle Fracture

Study Aim

The primary aim of this study was to evaluate the utility of bioimpedance analysis (BIA) as a non-invasive, quantifiable method for assessing soft tissue swelling in patients with acute ankle fractures. Swelling is a critical factor influencing surgical timing, postoperative recovery, and overall outcomes. Traditional methods such as circumference measurements and visual assessments are limited by their subjective nature and variability. By incorporating multifrequency BIA, the study sought to overcome these limitations and provide a more precise tool for monitoring swelling and its progression.

Specifically, the study aimed to (1) investigate the correlation between bioimpedance parameters (such as impedance ratio, reactance, and phase angle) and traditional circumference measurements, and (2) determine the temporal pattern of swelling resolution over the first 72 hours post-injury. A secondary aim was to assess the relationship between preoperative bioimpedance measurements and clinical outcomes, including wound healing and complication rates.

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Material and Methods

Subjects

Following approval from the Research Ethics Committee (IRB number: 110-016-F) at National Taiwan University Hospital, a prospective study was conducted involving 19 patients with ankle fractures. These patients were enrolled from the emergency department at the National Taiwan University Hospital Hsinchu Branch between April 2021 and March 2024. Inclusion criteria were patients over 20 years of age with an acute fracture (within 12 hours) of the ankle and the exclusion criteria included a history of prior lower extremity surgery, open fractures, and refusal to participate in the study.

Study design

Upon study enrollment, the circumference of both the injured and non-injured limbs was measured in the emergency department using a tape method. The measurements were taken at the medial malleolus.

Multifrequency bioimpedance measurements at 5kHz, 50kHz, 100kHz, and 200kHz, along with reactance and phase angle of both injured and uninjured lower extremities, were recorded at 12-hour intervals prior to surgery using the Quadscan 4000 (Bodystat, England). Electrode placement was as follows: the first electrode was positioned at the upper pole of the patella, the second 5 cm above the first, the third at

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the base of the second toe, and the fourth 5 cm proximal to the third (Fig3.). Additionally, time from injury to emergency department arrival, time to surgery, and postoperative wound complications, including antibiotic use, delayed wound healing, and wound necrosis, were documented.

Fig3. Illustration of the instrument (Quadscan 4000) and the position of electrodes for impedance measurement.

Results

Among the 19 enrolled patients, there were 8 men and 11 women, with an average age of 56.3 years. The cohort included 7 unimalleolar fractures, 7 bimalleolar fractures, and 5 trimalleolar fractures. The average time from injury to emergency department (ED) arrival was 4.5 hours, and the average time from injury to surgery was 37 hours. Postoperative wound complications were observed in 5 cases (Table 1).

A Spearman correlation coefficient of 0.736 was identified between the difference in ankle cross-sectional area and the impedance ratio at 5 kHz. The impedance ratio at 5 kHz between the injured and healthy limbs progressively decreased over time,

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measuring 81% at 0–12 hours, 80% at 13–24 hours, 75% at 24–36 hours, 73% at 37–48 hours, 71% at 49–60 hours, and 65% at 61–72 hours post-injury. A similar trend was observed across frequencies of 50, 100, and 200 kHz (Fig 4.) Among the 5 wound complications, 2 involved delayed healing, and 3 were superficial infections managed with oral antibiotics. The mean preoperative impedance ratio was 0.69 in patients with complications, compared to 0.82 in those without complications.

Table 1. Demographic data of ankle fracture patients (n=19)		
Age		56.3 (29-80)
Sex		
	M	8
	F	11
Side		
	R	10
	L	9
Fracture Type		
	Unimalleolar	7
	Bimalleolar	7
	Trimalleolar	5
Wound complications		
	Superficial infection	2
	Delayed healing	3
Time to ER (hours)		4.5
Time to surgery (hours)		37

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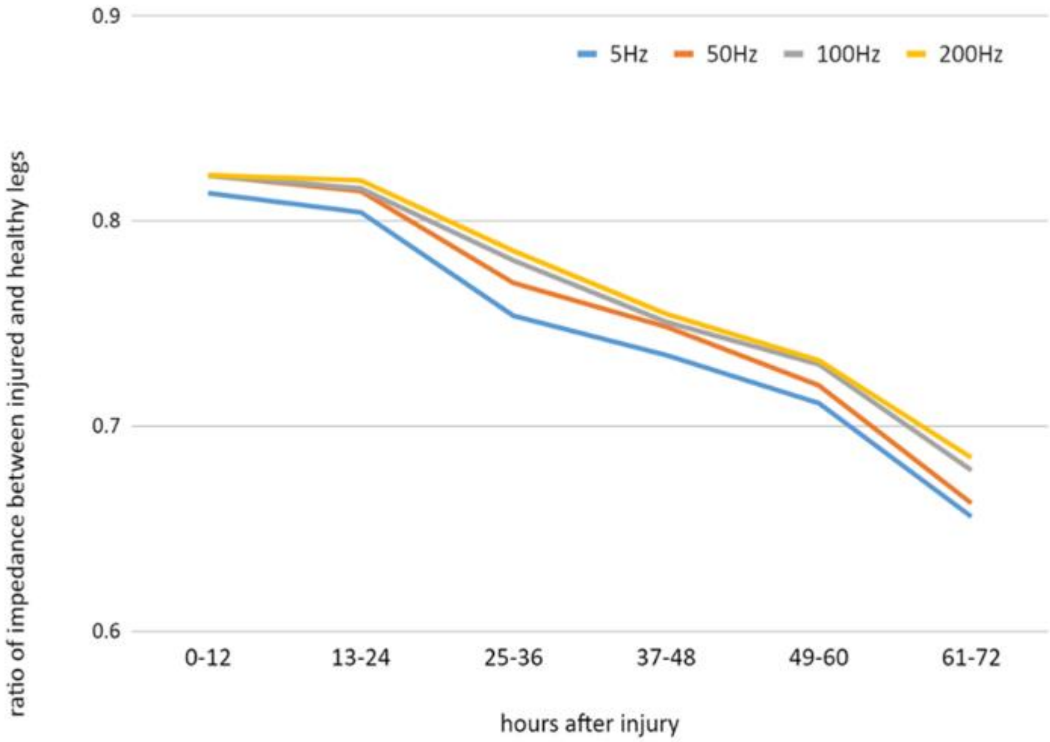

Fig4.The change of ratio of impedance between injured and healthy legs.

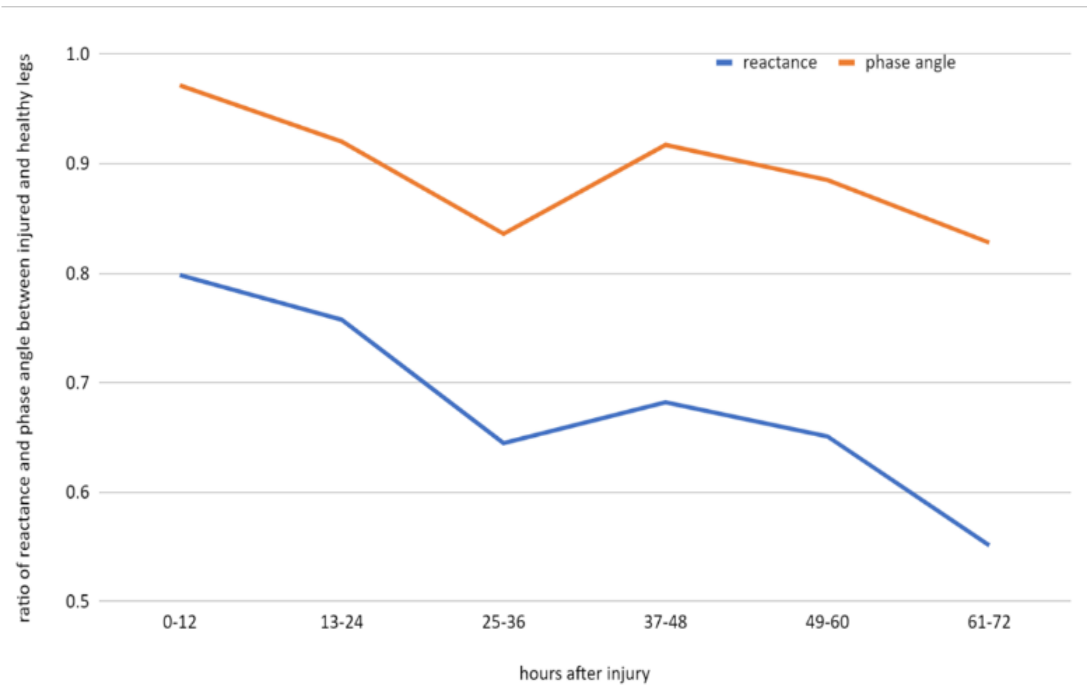

Fig5.The change of ratio of reactance and phase angle between injured and healthy legs.

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Discussion

Based on preliminary findings, the correlation coefficient between bioimpedance analysis (BIA) and circumferential measurement was 0.736, indicating a strong relationship. This result aligns with previous studies(14) and supports the feasibility of BIA as a method for assessing soft tissue swelling.

The bioimpedance ratio between the injured and healthy legs after ankle fractures demonstrated a continuous decrease across all frequencies during the first three days post-injury, suggesting progressive swelling over time. A similar trend was observed in reactance values, which may reflect not only interstitial edema but also cellular damage. Among the 19 patients studied, the majority underwent timely surgical intervention, with only two patients having surgery delayed beyond 72 hours. Consequently, the resolution phase of swelling, which is expected to occur around 120 hours post-injury, could not be comprehensively evaluated in this cohort.

All patients achieved eventual bony union without the need for revision surgery. However, five patients experienced minor complications: two with superficial infections and three with delayed wound healing. No severe adverse events were observed in this series. These minor complications are consistent with previous studies reporting infection rates of 4.4% to 10%(15). While the initial impedance ratio in the complication group was lower (0.69 vs. 0.82), the small sample size limited the

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statistical significance of this observation. Further studies with larger cohorts are needed to confirm these findings and better understand the relationship between impedance and clinical outcomes.

Summary

This study demonstrates the potential of bioimpedance analysis (BIA) as a reliable, non-invasive tool for assessing soft tissue swelling in patients with acute ankle fractures. The results showed a strong correlation (r = 0.736) between bioimpedance measurements and traditional circumference assessments, validating the feasibility of BIA in monitoring dynamic changes in swelling. The impedance ratio between injured and uninjured limbs progressively decreased over the first 72 hours post-injury, reflecting the progression of swelling and highlighting the utility of BIA in capturing tissue-level changes beyond conventional methods. While most patients experienced timely surgical interventions with successful outcomes, five minor wound complications were observed, which aligns with reported infection rates in similar clinical contexts. Importantly, the lower preoperative impedance ratios in patients with complications suggest that BIA parameters may serve as early indicators of potential adverse outcomes.

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Despite its promising findings, this study has limitations that warrant further investigation. The relatively small sample size restricts the generalizability of the results and limits the ability to explore the full resolution phase of swelling, particularly beyond the first 72 hours. Future studies should aim to include larger patient cohorts and extend the observation period to capture the entire course of swelling resolution. Furthermore, integrating BIA with other advanced imaging modalities, such as ultrasound or MRI, could provide a more comprehensive understanding of the interplay between tissue composition, fluid dynamics, and cellular health.

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Chapter 4. Methods for Swelling reduction.

Methods for Reducing Swelling After TKA

Various approaches have been developed to address postoperative swelling and improve patient recovery after TKA. These methods aim to control the inflammatory response, enhance lymphatic drainage, and prevent fluid accumulation. Common strategies include limb elevation, compression stockings(16), cryotherapy(17), manual lymphatic drainage(18), mechanical pumps(19) and electrostimulation(20). The principle of swelling reduction is similar to

Despite these interventions, a subset of patients continues to experience significant swelling, which may impede their recovery and long-term outcomes. This underscores the need for further research into innovative and integrative approaches to postoperative swelling management.

Photobiomodulation Therapy

1. Principles

Photobiomodulation therapy (PBMT), formerly known as low-level laser therapy (LLLT), is an innovative, non-invasive therapeutic technique that uses light energy to stimulate cellular function and promote healing. PBMT utilizes light energy, typically in the red (600–700 nm) or near-infrared (700–1100 nm) spectrum, to penetrate biological tissues. This light energy is absorbed primarily by chromophores, such as

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cytochrome c oxidase in the mitochondrial respiratory chain. The absorption of light energy leads to photophysical and photochemical reactions that modulate cellular function, a process known as photobiomodulation(21).

2. Mechanism of Action

The primary mechanism underlying PBMT involves the stimulation of mitochondrial activity(22), resulting in increased production of adenosine triphosphate (ATP). This boost in cellular energy enhances various physiological processes, including tissue repair, inflammation reduction, and pain modulation. Additionally, PBMT promotes the release of reactive oxygen species (ROS) and nitric oxide (NO), which play critical roles in cell signaling and vascular regulation(23). Together, these effects contribute to the therapeutic outcomes of PBMT, such as reduced edema, accelerated wound healing, and improved microcirculation(24). The mechanism of PBMT is illustrated as Fig 6.(25)

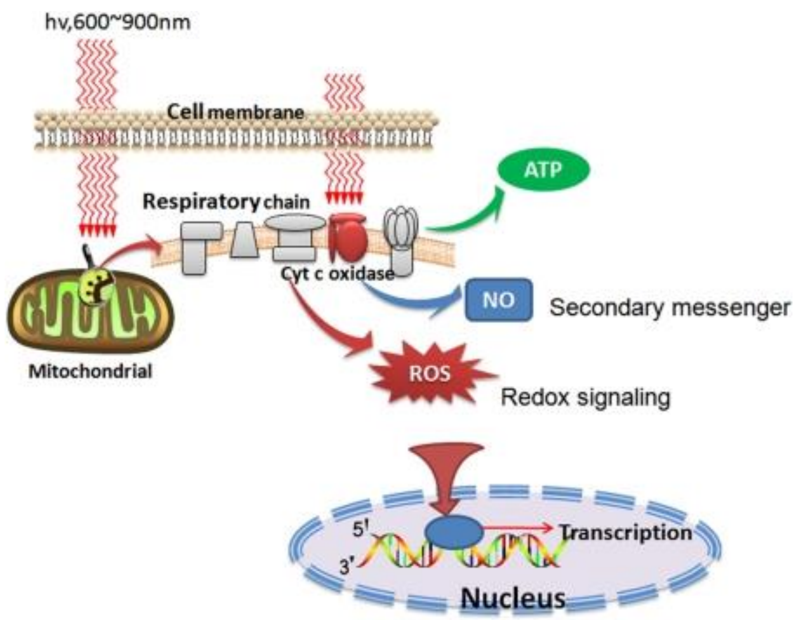

Fig6. Illustration of mechanism of PBMT.

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3. Dosage and Parameters

The effectiveness of PBMT heavily relies on accurately defining its dosage and parameters, as these determine the extent of tissue penetration and therapeutic response. Key parameters include wavelength, power density, energy density, pulse structure, and treatment duration, all of which must be tailored to the specific condition, tissue type, and depth of target structures.

1. Wavelength:

The wavelength of light determines its penetration depth into biological tissues. Red light (600–700 nm) is typically used for superficial tissues, as it penetrates up to 5–10 mm, while near-infrared (700–1100 nm) light is used for deeper tissues, reaching depths of up to 50 mm(21). For conditions such as musculoskeletal injuries or post-surgical recovery, near-infrared light is preferred to target deeper structures such as muscles, ligaments, and joints.

2. Power Density (Irradiance):

Power density, measured in milliwatts per square centimeter (mW/cm^2), refers to the intensity of light delivered to the tissue. The optimal range varies depending on the target tissue, but commonly applied values are between 5 and 500 mW/cm^2. Higher power densities may result in tissue heating, which can alter the therapeutic effects of PBMT (25).

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3. Energy Density (Fluence):

Energy density, expressed in joules per square centimeter (J/cm^2), is a crucial factor representing the total energy delivered per unit area. The biphasic dose-response relationship in PBMT suggests that low or excessive energy densities can lead to suboptimal outcomes. For clinical applications, energy densities between 4 and 10 J/cm^2 are effective for superficial tissues, while higher doses (10–50 J/cm^2) may be necessary for deeper tissues or chronic conditions(26).

4. Pulse Mode vs. Continuous Wave:

Light can be delivered in a continuous wave (CW) or pulsed mode. Pulsed delivery may enhance treatment effects by reducing tissue heating and increasing cellular stimulation. Frequencies in the range of 10–1000 Hz have been reported as beneficial for modulating pain and inflammation, although the specific frequency depends on the clinical condition(21).

5. Treatment Duration and Frequency:

The duration of light application per session and the frequency of treatment sessions significantly impact therapeutic outcomes. Typical treatment times range from 1 to 10 minutes per site, depending on the energy density and power output. Treatment frequency can vary, with acute conditions often requiring daily sessions, while chronic conditions may benefit from 2–3 sessions per week over a longer duration(27).

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6. Spot Size and Application Technique:

The size of the laser or LED beam, referred to as the spot size, affects the area treated and energy distribution. For larger treatment areas, a scanning or grid-like application technique ensures even coverage. Consistent probe-to-skin contact is necessary to minimize scattering and maximize tissue penetration(28).

7. Depth of Penetration and Target Tissue:

The optical properties of the target tissue—such as absorption and scattering—along with the wavelength and power density, influence the depth of light penetration. For example, water and melanin absorption are higher at shorter wavelengths, which may reduce penetration depth for red light compared to near-infrared light(21).

4. Clinical Applications of PBMT

Clinically, the efficacy of PBMT has been extensively studied in various orthopedic conditions. It has shown promising results in managing Achilles tendinopathy by reducing pain and promoting tissue healing (29), as well as in alleviating symptoms of knee osteoarthritis, where it helps decrease inflammation and improve joint function (30, 31). Additionally, PBMT has been demonstrated to effectively reduce postoperative pain following major orthopedic surgeries such as total hip and total knee arthroplasty, contributing to enhanced patient comfort and facilitating early mobilization(32, 33). Despite these encouraging findings, research

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specifically investigating PBMT’s impact on post-TKA swelling is still limited. This gap highlights the need for further studies to evaluate PBMT's potential as a non-invasive, adjunctive therapy for managing swelling and improving recovery outcomes after TKA.

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Chapter 5. Photobiomodulation Therapy in Total Knee Arthroplasty

Study Aim

Given the established utility of BIA for swelling measurement and evaluation, the present study aims to utilize BIA to determine the effectiveness of PBMT in reducing post-operative swelling at the early stage following TKA.

Study design

A single-center, nonblinded prospective randomized clinical trial compared PBMT and controls on postoperative swelling and functional outcomes after a primary TKA. The study's protocol was reviewed by our institutional review board and approved (111-036-F). The study was registered in the ClinicalTrials.gov (NCT06426251). This RCT followed the guidance of the Consolidated Standards of Reporting Trials (CONSORT) 2010.

Participants, study sample size, and randomization

From May to July 2024, patients undergoing TKA were prospectively enrolled at a single institution. The surgeries were performed by three surgeons (WZZ, CWD, HHC). Given the limited research on the effects of PBMT on BIA outcomes, the

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sample size was based on the study by Bahrami et al.(33), which explored the use of PBMT for post-TKA pain management and observed significant differences in swelling for 15 patients per group on postoperative day two, day three and 3 months. An effect size of approximately 0.76 was derived from the referenced study. According to findings by Pichonnaz et al.(34), bioimpedance changes are estimated to be 2-3 times greater than circumference changes in percentage terms. Based on this increased sensitivity, a target effect size of 1.2 was set for the present study. With an alpha level of 0.05 and a power of 0.80, a sample size of 12 patients per group was determined to be sufficient.

Block randomization was utilized with a block size of three. Random numbers for the randomization were generated using the Excel RAND function, and patients were divided into two groups across five blocks. Patients selected their group assignment via sealed envelopes. Due to the nature of the interventions involving distinct equipment, blinding was not feasible for patients, surgeons, or clinical medical staff. However, the researcher responsible for data analysis was blinded to group assignments. The process of enrollment and the subsequent procedures are detailed in the CONSORT flowchart (Fig.7).

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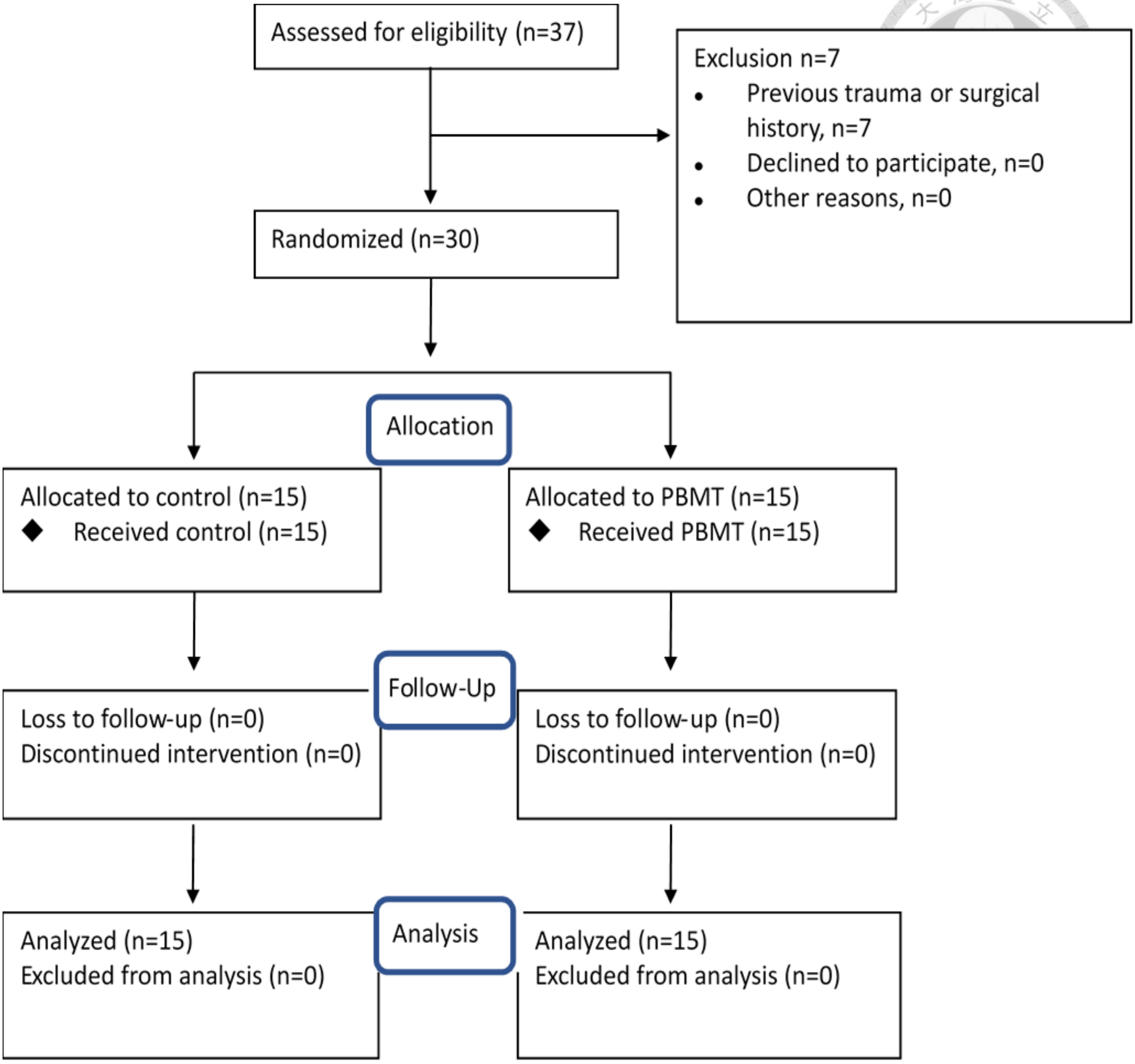

Fig7. CONSORT flowchart for patient enrollment and randomization.

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Inclusion and exclusion criteria

Inclusion criteria

- All patients aged over 20 underwent unilateral TKA in our institution during the period.

Exclusion criteria

- History of lower extremity surgery
- Skin defects over surgical site
- History of deep vein thrombosis, lymphedema, heart failure and chronic kidney disease
- Post-traumatic and rheumatoid arthritis
- Patients who declined to participate in the study
- Patients with cognitive impairment or those unable to fully comprehend the evaluation process

Study protocol

Control group

All patients in this study underwent a standard primary TKA utilizing the anterior midline incision and subvastus approach. Our institution adheres to the protocols of enhanced recovery after surgery (ERAS) for pre-surgery, perioperative, and

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postoperative care, which includes patient education, nutrition, pain management, and rehabilitation(35). Anesthesia was administered based on the anesthesiologist's decision, either as spinal or general. A pneumatic tourniquet was set at 300mmHg during surgery. Two types of implants were employed, chosen according to the surgeon's preference: the NexGen LPS-Flex by Zimmer Biomet Inc., based in Warsaw, IN, and another from United, Taiwan. From the first post-operative day (POD), patients began using a continuous passive motion (CPM) device starting at 60 degrees twice daily, with incremental adjustments of 5-10 degrees daily until POD6. A physical therapist was engaged from POD1 for guided rehabilitation. All patients started ambulating with a walker on POD1 and were discharged by POD6. They returned to the clinic for suture removal two weeks after the surgery. All patients were followed until post-operative 1 month.

Intervention group

Patients in the intervention group followed the same rehabilitation protocol as the control group, with the addition of PBMT using the Phototherapy System Mark II (Applied BioPhotonics, Hong Kong). This therapy commenced on POD1 and was administered daily until POD5. The PBMT involved a LED system that encompassed both the thigh and lower leg of the patient, with three square light pads, each measuring 10 centimeters per side, placed on each segment (Fig8). The settings for

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the system were as follows: it emitted light at wavelengths of 650nm and 850nm, with power densities of 8.4 and 13.5mW per cm2 for each respective wavelength and the working duration for each wavelength was set to 30 minutes. The LEDs, each with a different wavelength, were evenly arranged in an alternating pattern across the square pad. The pulse frequency ranged from 100 to 1000Hz, and the duty cycle was set at 50%. Each daily session of light therapy lasted 60 minutes. The summary of parameters of PBMT was shown in table 2. Further details regarding the instrument can be found in US Patent US20180169431A1, titled 'Flexible LED Light Pad for Phototherapy.

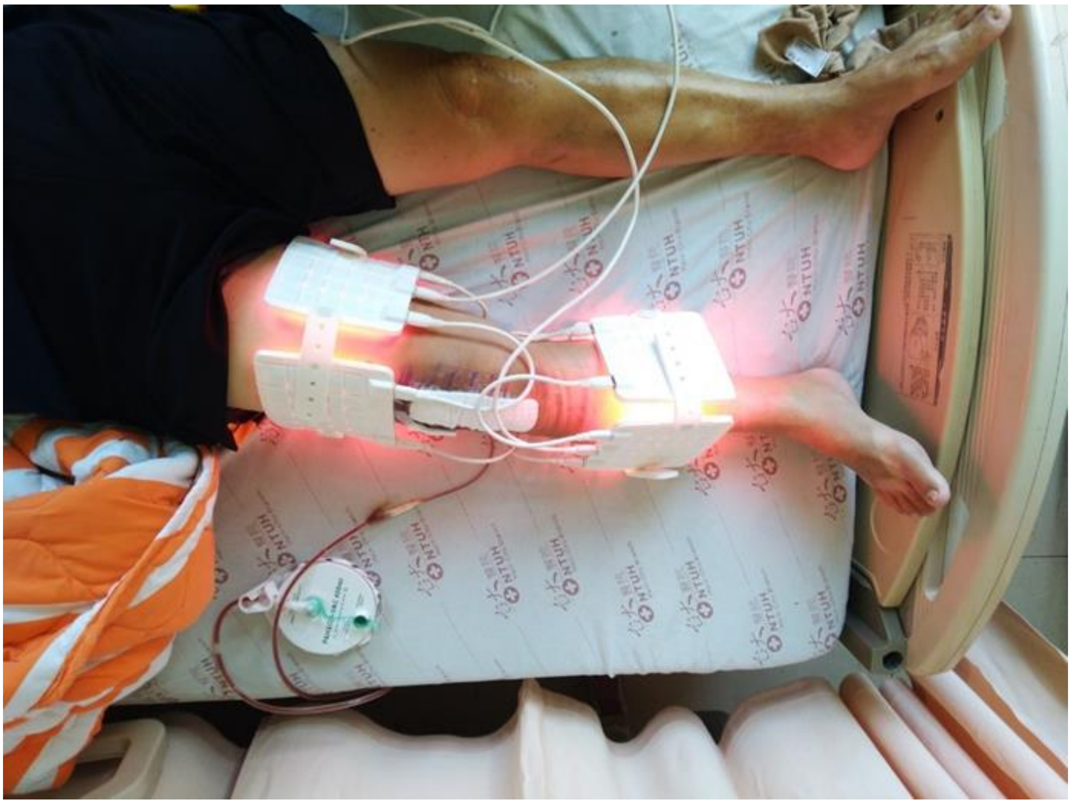

Fig 8. Demonstration of photobiomodulation therapy of the operated leg with the peds composed of light emitting diodes.

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Table 2. Summary of the parameters of PBMT.

Wavelength	nm	650	850
Frequency 101-500Hz	mins	10	10
Frequency 501-1000Hz	mins	10	10
Frequency >1000Hz	mins	10	10
Duty cycle	%	50	50
Power density	mW.cm^2	8.4	13.5
Energy density	j/cm^2	15.2	24.3

Swelling evaluation - bioimpedance analysis

All patients underwent localized BIA using the Quadscan 4000 system (Bodystat, England) from the POD1 to POD6, and again at POD14. Measurements were taken at 8am each day. The procedure involved placing four leads on both the operated and non-operated limbs. The positioning of the leads was as follows: the first lead was placed 10 cm above the patella's upper tip, the second lead was positioned 5 cm proximal to the first, the third lead at the base of the second toe, and the fourth lead 5 cm proximal to the third (Fig8). The analysis included several variables across four different frequencies (5 kHz, 50 kHz, 100 kHz, and 200 kHz), along with measurements of reactance and phase angle. At a low frequency of 5 kHz, the electrical current travels through the extracellular fluid without penetrating the cell membrane, whereas at higher frequencies (above 50 kHz), the current passes through

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both intra- and extracellular fluids(11). Reactance measures the cell membranes' capacitance, and phase angle is calculated as the arctangent of the reactance to resistance ratio, serving as an indicator of cellular health. Higher phase angle values indicate better cellular integrity and function(36, 37). Post-surgical edema, hematoma, and tissue damage typically reduce resistance and reactance, leading to lower impedance values. To minimize biases related to overall body fluid status, the ratio of impedance measurements between the two legs was calculated. The primary outcome was the impedance ratio on POD6 with POD1serving as the baseline reference (POD6/POD1), chosen to reduce the individual variability from surgical effects.

Clinical outcome measurement

Three clinical variables were assessed on POD1 and again on POD6. These included the patient self-reported visual analogue score (VAS) for pain, the active range of motion (aROM) of the knee, and the 2-minute walk test (2MWT). The VAS consists of a 100 mm line marked at each end with descriptors representing the extremes of pain: 'no pain' at 0 mm and 'worst imaginable pain' at 100 mm. The score is determined by measuring the distance between patient’s mark and the 0 mm(38). For measuring aROM, patients were positioned supine, and the knee angle was determined using a goniometer. The angle was measured between two lines: one from

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the greater trochanter to the lateral femoral condyle, and the other from the lateral femoral condyle to the lateral malleolus. The 2MWT was conducted in a long corridor marked at one-meter intervals. Patients were instructed to walk as quickly as possible using a walker for two minutes, and the distance covered was recorded.

Statistical Method

Continuous variables were initially evaluated for normality with the Shapiro-Wilk test. For data conforming to a normal distribution, comparisons between the control and PBMT groups were made using the t-test. For data not normally distributed, the Wilcoxon rank sum test was employed. Categorical data were analyzed using Fisher's exact test. Continuous repeated measures data were analyzed using repeated measures ANOVA for parametric data and the Friedman test for non-parametric data. All statistical analyses were conducted using SPSS software, version 25.0 (SPSS Inc, Chicago, IL, USA). A p-value of less than 0.05 was considered statistically significant.

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Results

The demographic data, including age, BMI, surgical duration, and anesthesia methods, showed no significant differences between the control and PBMT groups (Table 3). Both groups experienced no wound infections, dehiscence, or thromboembolic events, and all wounds healed uneventfully by two weeks post-surgery.

Table 3. Demographic data of PBMT on swelling reduction after TKA

	Control	Photobiomodulation	p-value
Number	15	15	
Age (year)	69.9 ±5.8	70.4 ± 9.1	0.869
Sex			
M	3	6	0.427
F	12	9	
BMI	26.8 ± 3.2	26.5 ± 4.5	0.840
Side			
L	10	5	0.143
R	5	10	
Operative time (min)	91.2 ± 6.8	98.1 ± 13.3	0.086
Anesthesia			
General	10	8	0.71
Spinal	5	7	

The data were presented as Mean ± Standard Deviation

BMI, body mass index

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Swelling evaluation

At POD6, with POD1 as the reference (POD6/POD1), the ratios of impedance, reactance, and phase angle between the operative and non-operative legs were lower in the PBMT group compared to the control group across various frequencies, showing differences of 0.158, 0.14, 0.133, 0.131, 0.197 and 0.07 for impedance at 5kHz, 50kHz, 100kHz, 200kHz, reactance and phase angle respectively (Table 4). From POD1 to POD6, there were no significant changes in these ratios within the PBMT group, whereas the control group exhibited a gradual decrease. The discrepancies in ratios between the control and PBMT groups remained consistent at both POD6 and POD14 (Figure 9).

Table 4. The comparison of bioimpedance ratio between operative and contralateral leg at POD6 with POD1 as reference (POD6/POD1)

	Control group	PBM group	difference	p-value
5K	0.841	0.99	0.158	<0.001
50K	0.847	0.987	0.14	<0.001
100K	0.853	0.986	0.133	<0.001
200K	0.857	0.988	0.131	<0.001
Reactance	0.796	0.993	0.197	<0.001
Phase angle	0.939	1.009	0.07	0.026

POD means-post operative day

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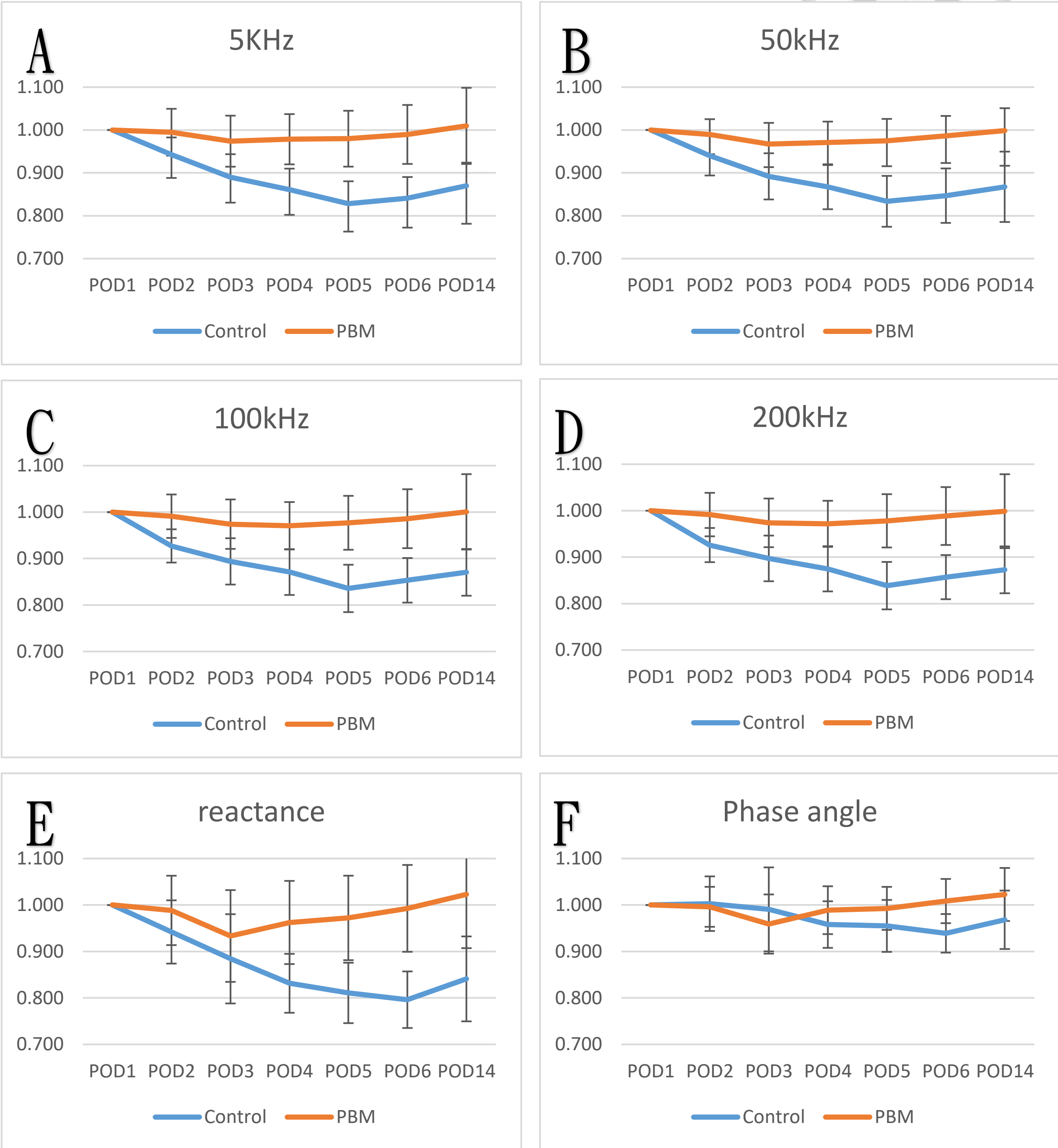

Fig 9. Comparison of daily changes in impedance ratios at 5kHz, 50kHz, 100kHz, and 200kHz, as well as reactance and phase angle ratios between the operative and ipsilateral leg, using POD1 as the baseline (ratio equals PODn/POD1) for both the control group and the PBMT group. The error bar represents 95% confidence interval.

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Clinical outcome difference

For clinical outcomes, no significant differences were observed between the control and PBMT groups in VAS scores (5.5 vs. 5.8), aROM (27 degrees vs. 33 degrees), and 2MWT (6.9 meters vs. 7 meters) on POD1. By POD6, the PBMT group achieved a longer walking distance in the 2MWT compared to the control group (27 meters vs. 16 meters). However, there were no significant differences in aROM or VAS scores between the groups at this time point (Table 5).

Table 5. Clinical outcome difference between control and photobiomodulation group

	Control	Photobiomodulation	p-value
VAS POD1	5.5	5.8	0.569
VAS POD6	2.9	2.7	0.605
aROM POD1	27.0	33.0	0.131
aROM POD6	61.3	68.3	0.258
2MWT POD1	6.9	7	0.918
2MWT POD6	16	27	0.009

aROM, active range of motion; 2MWT, 2-minute walk test; VAS, visual analogue scale of pain

aROM presented as degree, 2MWT presented as meter

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Discussions

This study demonstrates the efficacy of PBMT in reducing post-operative swelling and improving functional mobility in the acute stage following TKA. Our results indicate a 15% reduction in impedance from the POD1 to POD6, alongside a 69% improvement in walking distance as measured by the 2MWT at POD6. Additionally, the benefits of swelling reduction were sustained up to two weeks post-operatively. This is the first known study to investigate the impact of PBMT on reducing acute post-operative swelling following TKA.

Early rehabilitation following TKA has been previously shown to facilitate quicker recovery of walking ability, enhance strength, and improve short-term outcome(39-41). However, post-operative swelling typically increases by approximately 10% within the first three days and peaks between days 6 and 8(42), which can impede early rehabilitation efforts. Our findings align with these observations; the control group exhibited a gradual decrease in impedance, reactance, and phase angle from POD1 to POD6, with only a mild recovery noted by POD14. The bioimpedance ratio decreased by approximately 15% from POD1 to POD6, aligning with findings from a previous study that reported a 12% reduction from POD2 to POD8(34). Conversely, the PBMT group showed less decline in these measurements from POD2 to POD3 and demonstrated quicker recovery from POD4

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to POD6 and the bioimpedance ration decreased only 1.5% from POD1 to POD6. The correlation between changes in reactance and phase angle with impedance suggests that swelling improvement may not only be due to the reduction of extracellular edema but also enhanced cellularity and cellular function, potentially fostered by the mechanisms of PBMT that promote healing and increase circulation.

Clinically, while the 6-minute walk test (6MWT) is a recognized measure of functional capacity in joint replacement and osteoarthritis(43), it is often too demanding for elderly patients in the acute post-operative period. Consequently, we employed the 2MWT, which has shown excellent correlation with the 6MWT and offers a more feasible alternative for this patient population(44). The results revealed that the PBMT group achieved longer walking distances compared to the control group. This improvement may not only result from PBMT's ability to reduce swelling but also from its enhancement of wound healing, improvement of local circulation, and reduction of inflammation. Although PBMT is known for its post-operative pain reduction capabilities(32, 45, 46), our study did not show significant differences in pain scores, possibly due to the resting condition during pain assessment. Besides, our institution’s multimodal pain management and early rehabilitation protocols have effectively reduced patient pain, as demonstrated by a 2.9-point improvement in pain scores observed in the control group, which may obscure detectable differences

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between the PBMT and control groups. Regarding aROM, no significant difference was observed between the control and PBMT groups, potentially due to the routine application of continuous passive motion (CPM) in our institution. By POD6, all patients achieved approximately 100 degrees of flexion and 10 degrees of extension through progressive daily CPM adjustments. This considerable range of motion may have limited the ability to detect additional effects of PBMT on aROM.

This study has several limitations. Firstly, the sample size was determined based on the effect of PBMT on post-TKA pain reduction, which serves as an indirect measure of impedance changes. The relatively small sample size may limit the statistical power of our analyses. Secondly, bioimpedance analysis, while useful, does not provide exact measurements of volume changes nor does it distinctly differentiate between cellular responses and the amount of extracellular fluid. A more comprehensive evaluation at the molecular and cellular levels would be necessary to accurately assess the swelling condition. Third, there is no established consensus on the parameters for PBMT, including power density, duration, pulse frequency, and duty cycle. Variations in these settings can lead to different clinical outcomes. Additional research is needed to determine the optimal parameters for PBMT.

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Summary

The results of this study suggest that PBMT is a safe and non-invasive method for reducing postoperative swelling in the early phases after TKA. When combined with modern early rehabilitation protocols and multimodal pain management, PBMT has potential as an adjunct rehabilitation tool to promote early recovery and accelerate functional improvement. Nevertheless, to validate PBMT as a standardized treatment for post-TKA swelling management, additional data from larger, randomized controlled trials are required.

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Chapter 6. Conclusion and Future Expectation

The integration of bioimpedance analysis (BIA) and photobiomodulation therapy (PBMT) into orthopedic surgery represents a groundbreaking advancement with the potential to significantly improve postoperative management and outcomes. BIA offers a non-invasive, highly precise method for tracking changes in tissue composition, fluid balance, and cellular health, enabling surgeons and clinicians to identify complications such as edema or delayed wound healing. Its future applications could include refining surgical planning, tailoring rehabilitation strategies to individual patients, and optimizing the timing of critical interventions. On the other hand, PBMT provides a cutting-edge approach to reducing inflammation, promoting tissue regeneration, and mitigating pain following procedures like joint replacements or fracture repairs. By enhancing cellular recovery and supporting faster edema resolution, PBMT could lead to shorter recovery timelines and improved functional outcomes. Looking ahead, research should aim to establish standardized protocols for both technologies, improve their ease of use, and explore their combined effects on a wider range of musculoskeletal conditions. Together, BIA and PBMT have the potential to redefine orthopedic care by enabling data-driven, personalized treatment plans that prioritize patient recovery and quality of life.

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References

1. Tull F, Borrelli Jr J. Soft-tissue injury associated with closed fractures: evaluation and management. JAAOS-Journal of the American Academy of Orthopaedic Surgeons. 2003;11(6):431-8.
2. Miller AG, Margules A, Raikin SM. Risk factors for wound complications after ankle fracture surgery. JBJS. 2012;94(22):2047-52.
3. Holm B, Kristensen MT, Bencke J, Husted H, Kehlet H, Bandholm T. Loss of knee-extension strength is related to knee swelling after total knee arthroplasty. Archives of physical medicine and rehabilitation. 2010;91(11):1770-6.
4. Loyd BJ, Stackhouse S, Dayton M, Hogan C, Bade M, Stevens-Lapsley J. The relationship between lower extremity swelling, quadriceps strength, and functional performance following total knee arthroplasty. The Knee. 2019;26(2):382-91.
5. Noble PC, Conditt MA, Cook KF, Mathis KB. The John Insall Award: Patient expectations affect satisfaction with total knee arthroplasty. Clinical Orthopaedics and Related Research (1976-2007). 2006;452:35-43.
6. O Driscoll SW, Giori NJ. Continuous passive motion (CPM): theory and principles of clinical application. Journal of rehabilitation research and development. 2000;37(2):179-88.
7. Yau LK, Henry F, Man Hong C, Amy C, Wai Kwan Vincent C, Ping Keung C, et al. Swelling assessment after total knee arthroplasty. Journal of Orthopaedic Surgery. 2022;30(3):10225536221127668.
8. Schaser KD, Vollmar B, Menger MD, Schewior L, Kroppenstedt SN, Raschke M, et al. In vivo analysis of microcirculation following closed soft-tissue injury. Journal of orthopaedic research. 1999;17(5):678-85.
9. Bakar Y, Özdemir Ö, Sevim S, Duygu E, Tuğral A, Sürmeli M. Intra-observer and inter-observer reliability of leg circumference measurement among six observers: a single blinded randomized trial. Journal of medicine and life. 2017;10(3):176.
10. Riedel MD, Parker A, Zheng M, Briceno J, Staffa SJ, Miller CP, et al. Correlation of soft tissue swelling and timing to surgery with acute wound complications for operatively treated ankle and other lower extremity fractures. Foot & Ankle International. 2019;40(5):526-36.
11. Kyle UG, Bosaeus I, De Lorenzo AD, Deurenberg P, Elia M, Gómez JM, et al. Bioelectrical impedance analysis—part I: review of principles and methods. Clinical nutrition. 2004;23(5):1226-43.
12. van der Sande FM, van de Wal-Visscher ER, Stuard S, Moissl U, Kooman JP. Using bioimpedance spectroscopy to assess volume status in dialysis patients. Blood purification. 2020;49(1-2):178-84.

doi:10.6342/NTU202500002

13. Norman K, Stobäus N, Pirlich M, Bosy-Westphal A. Bioelectrical phase angle and impedance vector analysis–clinical relevance and applicability of impedance parameters. Clinical nutrition. 2012;31(6):854-61.
14. King RJ, Clamp JA, Hutchinson JW, Moran CG. Bioelectrical impedance: a new method for measuring post-traumatic swelling. Journal of orthopaedic trauma. 2007;21(7):462-8.
15. Vanderkarr MF, Ruppenkamp JW, Vanderkarr M, Parikh A, Holy CE, Putnam M. Incidence, costs and post-operative complications following ankle fracture–A US claims database analysis. BMC Musculoskeletal Disorders. 2022;23(1):1129.
16. Munk S, Jensen NJ, Andersen I, Kehlet H, Hansen TB. Effect of compression therapy on knee swelling and pain after total knee arthroplasty. Knee Surgery, Sports Traumatology, Arthroscopy. 2013;21(2):388-92.
17. Wyatt PB, Nelson CT, Cyrus JW, Goldman AH, Patel NK. The role of cryotherapy after total knee arthroplasty: a systematic review. The Journal of Arthroplasty. 2023;38(5):950-6.
18. Lu H, Shao Q, Li W, Li F, Xiong W, Li K, et al. Effects of manual lymphatic drainage on total knee replacement: a systematic review and meta-analysis of randomized controlled trials. BMC Musculoskeletal Disorders. 2024;25(1):30.
19. Wickline A, Cole W, Melin M, Ehmann S, Aviles F, Bradt J. Mitigating the Post-Operative Swelling Tsunami in Total Knee Arthroplasty: A Call to Action. Journal of Orthopaedic Experience & Innovation. 2023.
20. Yue C, Zhang X, Zhu Y, Jia Y, Wang H, Liu Y. Systematic review of three electrical stimulation techniques for rehabilitation after total knee arthroplasty. The journal of arthroplasty. 2018;33(7):2330-7.
21. Hamblin MR. Mechanisms and applications of the anti-inflammatory effects of photobiomodulation. AIMS biophysics. 2017;4(3):337.
22. Zungu IL, Hawkins Evans D, Abrahamse H. Mitochondrial responses of normal and injured human skin fibroblasts following low level laser irradiation—an in vitro study. Photochemistry and Photobiology. 2009;85(4):987-96.
23. da Silva TG, Ribeiro RS, Mencalha AL, de Souza Fonseca A. Photobiomodulation at molecular, cellular, and systemic levels. Lasers in Medical Science. 2023;38(1):136.
24. De Oliveira MF, Johnson DS, Demchak T, Tomazoni SS, Ernesto C. Low-intensity LASER and LED (photobiomodulation therapy) for pain control of the most common musculoskeletal conditions. European journal of physical and rehabilitation medicine. 2022;58(2):282.
25. Huang Y-Y, Chen AC-H, Carroll JD, Hamblin MR. Biphasic dose response in low level light therapy. Dose-response. 2009;7(4):dose-response. 09-027. Hamblin.

doi:10.6342/NTU202500002

26. Leal ECP, Lopes-Martins RÁB, Frigo L, De Marchi T, Rossi RP, De Godoi V, et al. Effects of low-level laser therapy (LLLT) in the development of exercise-induced skeletal muscle fatigue and changes in biochemical markers related to postexercise recovery. journal of orthopaedic & sports physical therapy. 2010;40(8):524-32.
27. Bjordal JM, Couppé C, Chow RT, Tunér J, Ljunggren EA. A systematic review of low level laser therapy with location-specific doses for pain from chronic joint disorders. Australian journal of physiotherapy. 2003;49(2):107-16.
28. Beckerman H, de Bie RA, Bouter LM, De Cuyper HJ, Oostendorp RA. The efficacy of laser therapy for musculoskeletal and skin disorders: a criteria-based meta-analysis of randomized clinical trials. Physical therapy. 1992;72(7):483-91.
29. Atik OS. Photobiomodulation for Achilles Tendinopathy. Photomedicine and laser surgery. 2017;36(1):1-2.
30. Ahmad MA, Hamid MSA, Yusof A. Effects of low-level and high-intensity laser therapy as adjunctive to rehabilitation exercise on pain, stiffness and function in knee osteoarthritis: a systematic review and meta-analysis. Physiotherapy. 2022;114:85-95.
31. Stausholm MB, Naterstad IF, Joensen J, Lopes-Martins RÁB, Sæbø H, Lund H, et al. Efficacy of low-level laser therapy on pain and disability in knee osteoarthritis: systematic review and meta-analysis of randomised placebo-controlled trials. BMJ open. 2019;9(10):e031142.
32. Langella LG, Casalechi HL, Tomazoni SS, Johnson DS, Albertini R, Pallotta RC, et al. Photobiomodulation therapy (PBMT) on acute pain and inflammation in patients who underwent total hip arthroplasty—a randomized, triple-blind, placebo-controlled clinical trial. Lasers in medical science. 2018;33:1933-40.
33. Bahrami H, Moharrami A, Mirghaderi P, Mortazavi SMJ. Low-level laser and light therapy after total knee arthroplasty improves postoperative pain and functional outcomes: a three-arm randomized clinical trial. Arthroplasty Today. 2023;19:101066.
34. Pichonnaz C, Bassin J-P, Lécureux E, Currat D, Jolles BM. Bioimpedance spectroscopy for swelling evaluation following total knee arthroplasty: a validation study. BMC Musculoskeletal Disorders. 2015;16:1-8.
35. Riga M, Altsitzioglou P, Saranteas T, Mavrogenis AF. Enhanced recovery after surgery (ERAS) protocols for total joint replacement surgery. SICOT-J. 2023;9.
36. Yamada Y, Yoshida T, Murakami H, Kawakami R, Gando Y, Ohno H, et al. Phase angle obtained via bioelectrical impedance analysis and objectively measured physical activity or exercise habits. Scientific reports. 2022;12(1):17274.
37. Akamatsu Y, Kusakabe T, Arai H, Yamamoto Y, Nakao K, Ikeue K, et al. Phase angle from bioelectrical impedance analysis is a useful indicator of muscle quality. Journal of cachexia, sarcopenia and muscle. 2022;13(1):180-9.

doi:10.6342/NTU202500002

38. Hawker GA, Mian S, Kendzerska T, French M. Measures of adult pain: Visual analog scale for pain (vas pain), numeric rating scale for pain (nrs pain), mcgill pain questionnaire (mpq), short-form mcgill pain questionnaire (sf-mpq), chronic pain grade scale (cpgs), short form-36 bodily pain scale (sf-36 bps), and measure of intermittent and constant osteoarthritis pain (icoap). Arthritis care & research. 2011;63(S11):S240-S52.
39. Lisi C, Caspani P, Bruggi M, Carlisi E, Scolè D, Benazzo F, et al. Early rehabilitation after elective total knee arthroplasty. Acta Bio Medica: Atenei Parmensis. 2017;88(Suppl 4):56.
40. Sattler L, Hing W, Vertullo C. Changes to rehabilitation after total knee replacement. Australian journal of general practice. 2020;49(9):587-91.
41. Konnyu KJ, Thoma LM, Cao W, Aaron RK, Panagiotou OA, Bhuma MR, et al. Rehabilitation for total knee arthroplasty: a systematic review. American journal of physical medicine & rehabilitation. 2023;102(1):19-33.
42. Loyd BJ, Kittelson AJ, Forster J, Stackhouse S, Stevens-Lapsley J. Development of a reference chart to monitor postoperative swelling following total knee arthroplasty. Disability and Rehabilitation. 2020;42(12):1767-74.
43. Bennell K, Dobson F, Hinman R. Measures of physical performance assessments: self-paced walk test (SPWT), stair climb test (SCT), six-minute walk test (6MWT), chair stand test (CST), timed up & go (TUG), sock test, lift and carry test (LCT), and car task. Arthritis care & research. 2011;63(S11):S350-S70.
44. Gacto-Sánchez M, Lozano-Meca JA, Lozano-Guadalajara JV, Montilla-Herrador J. Concurrent validity of the 2-and 6-minute walk test in knee osteoarthritis. The Knee. 2023;43:34-41.
45. Ezzati K, Fekrazad R, Raoufi Z. The effects of photobiomodulation therapy on post-surgical pain. Journal of lasers in medical sciences. 2019;10(2):79.
46. Rezende MUd, Varone BB, Martuscelli DF, Ocampos GP, Freire GMG, Pinto NC, et al. Pilot study of the effect of therapeutic photobiomodulation on postoperative pain in knee arthroplasty. Brazilian Journal of Anesthesiology. 2022;72:159-61.

doi:10.6342/NTU202500002