The Effect of TECAR Therapy, Extracorporeal Shock Wave Therapy and Complete Decongestive Therapy in the Treatment of Bilateral Lower-Limb Secondary Lymphedema in Severely Obese Patients: A Prospective Randomized Controlled Study

Abstract

Background: Lymphedema associated with severe obesity is a progressive condition characterized by bilateral lower-limb swelling, functional impairment and reduced quality of life. Complex Decongestive Therapy (CDT) remains the standard treatment, but its effectiveness in obesity-related lymphedema is limited. Adjunctive therapies such as Transfer Energy Capacitive and Resistive therapy (TECAR) and Extracorporeal Shock Wave Therapy (ESWT) may enhance outcomes by targeting distinct pathophysiological mechanisms.

Objective: To compare the effectiveness of CDT alone versus CDT combined with TECAR or ESWT in reducing limb circumference, improving quality of life, alleviating pain and decreasing tissue stiffness in severely obese patients with bilateral lower-limb lymphedema.

Methods: In this prospective randomized controlled trial, 45 female patients (BMI ≥40 kg/m²) with bilateral lower-limb lymphedema were allocated to CDT alone, CDT+TECAR, or CDT+ESWT groups (n=15 each). All groups received standardized CDT protocols for 4 weeks. TECAR was applied five times weekly, while ESWT was delivered three times weekly. Outcomes included limb circumference, Lymphedema Quality of Life Questionnaire (LYMQOL), pain intensity (VAS), and tissue stiffness (tonometry), assessed at baseline, 4 weeks, and 8 weeks. Data were analyzed using two-way mixed ANOVA (Group × Time) with Greenhouse-Geisser correction, followed by Bonferroni-adjusted post-hoc comparisons. Effect sizes (partial eta squared and Cohen's d) and 95% confidence intervals were reported.

Results: A significant Group × Time interaction was observed for all outcomes ($p < 0.001$). For left ankle circumference, the mean reduction from baseline to 4 weeks was −2.82 cm (95% CI: −2.88, −2.76) in CDT, −3.92 cm (95% CI: −3.99, −3.85) in CDT+TECAR, and −4.51 cm (95% CI: −4.60, −4.43) in CDT+ESWT (interaction $\eta p^2 = 0.957$). Between-group effect sizes at 4 weeks were large (Cohen's d: CDT vs CDT+ESWT = 1.83; CDT

vs CDT+TECAR = 1.37). VAS pain reduction was significantly greater in CDT+ESWT versus CDT (mean difference = 0.83, 95% CI: 0.66–1.01, d = 3.54). Overall LYMQOL improvement favored CDT+ESWT over CDT (d = 7.29). Benefits were sustained at 8 weeks, though modest deterioration was observed. No serious adverse events occurred.

Conclusion: Both TECAR and ESWT significantly enhance CDT outcomes in severely obese patients with bilateral lower-limb lymphedema. ESWT demonstrated the most pronounced benefits with large effect sizes, suggesting its potential as a preferred adjunctive therapy. These findings support integrating adjunctive modalities into standard CDT protocols to optimize outcomes in this challenging patient population.

Trial Registration: [Reg. No. SREC.PT.SUE (19) 1025]; date of registration: 25/10/2025.

Keywords: Secondary lymphedema; Severe obesity; Complex decongestive therapy; Extracorporeal shock wave therapy; Transfer energy capacitive and resistive therapy

Background

Lymphedema is a chronic, progressive condition characterized by protein-rich fluid accumulation, limb swelling, functional impairment, and reduced quality of life [1]. While cancer-related lymphedema has been extensively studied, obesity-associated lymphedema remains underrecognized despite its rising prevalence. Severe obesity both predisposes to lymphatic dysfunction and worsens treatment outcomes once lymphedema develops [2,3].

Prevalence increases sharply with body mass index, affecting around 6% of individuals with BMI <50 kg/m² and nearly 90% of those with BMI ≥60 kg/m² [4]. Unlike the typically unilateral presentation of cancer-related lymphedema, obesity-related disease is usually bilateral, creating distinct therapeutic challenges [5].

Complex decongestive therapy (CDT) is the gold standard treatment across etiologies [6]. This multimodal approach, including manual lymphatic drainage, compression bandaging, exercise and skin care, has proven efficacy but limited effectiveness in obesity-related lymphedema. Obese patients often show reduced response, with some reverting to baseline volumes within one year [7,8]. Pathophysiological features such as chronic inflammation, tissue fibrosis, and adipose deposition further compromise CDT outcomes [9].

Adjunctive therapies have therefore gained attention. Transfer energy capacitive and resistive therapy (TECAR) delivers radiofrequency energy to generate endogenous tissue heating, promoting vasodilation, microcirculation, and potentially lymphatic drainage [10]. Preliminary studies suggest TECAR achieves faster volume reduction than manual drainage, though controlled trials remain scarce [11]. Extracorporeal shock wave therapy (ESWT), widely used in musculoskeletal disorders, stimulates lymphangiogenesis via VEGF-C/VEGFR-3 upregulation and reduces fibrosis through collagen modulation [12–16]. Clinical studies in breast cancer-related lymphedema report sustained volume reduction and tissue softening, but evidence in obesity-related lower-limb disease is limited.

Obesity-related lymphedema is increasingly recognized as a separate clinical condition in which excessive body weight contributes to a gradual decline in lymphatic system function. Evidence from clinical assessment and

imaging studies indicates a reduction in lymphatic drainage capacity that correlates with rising body mass index. The disorder typically manifests with bilateral involvement of the lower extremities and is often difficult to manage, especially in individuals with advanced obesity [17].

Lymphedema is a long-standing, progressive disorder characterized not only by fluid retention but also by irreversible structural alterations within the affected tissues. Ongoing impairment of lymphatic function promotes chronic inflammation, increased fat accumulation, and fibrotic changes leading to reduced tissue elasticity and diminished response to conventional decongestive treatment. These pathological changes tend to be more severe in late-stage disease and in cases associated with obesity [18].

However, most studies focus on upper-limb cancer-related lymphedema; comparative effectiveness data are lacking, and objective assessment of tissue quality has been underexplored. Therefore, this trial was designed to address these gaps by comparing CDT alone with CDT combined with TECAR or ESWT in severely obese patients with bilateral lower-limb lymphedema. Both adjunctive therapies were expected to enhance outcomes beyond standard complex decongestive therapy, with primary emphasis on limb circumference reduction and secondary outcomes including quality of life, pain intensity, and tissue stiffness. The results are anticipated to contribute to clinical decision-making and to advance understanding of optimal therapeutic strategies for patients with obesity-related bilateral lower-limb lymphedema.

Methods

Study Design and Participants

This prospective randomized controlled trial was conducted between 25 October 2025 and 6 February 2026 at Modawah Physical Therapy Center, Beni Suef, Egypt. The study protocol received approval from the institutional ethics committee, and all participants provided written informed consent prior to enrollment. The trial was registered at Al Salam University, Faculty of Physical Therapy, Scientific Research Ethics Committee under the identification number No: SREC.PT.SUE (19)1025. The study is reported according to the Consolidated Standards of Reporting Trials (CONSORT) guidelines, and the CONSORT flow diagram is presented in **Figure 5.**

Female patients aged 18–75 years with bilateral lower limb lymphedema secondary to severe obesity (BMI ≥40 kg/m²) were eligible for inclusion. Lymphedema diagnosis required clinical assessment by an experienced lymphedema specialist and confirmation of bilateral limb swelling with pitting or non-pitting edema extending above the ankle. Additional inclusion criteria included lymphedema duration of at least 3 months and the ability to attend treatment sessions five times weekly for 4 weeks, plus follow-up assessments.

Exclusion criteria encompassed secondary lymphedema due to other causes (malignancy, radiation, surgery, infection), primary lymphedema, acute deep vein thrombosis or history of recurrent thrombosis, active infection or cellulitis, peripheral arterial disease with ankle-brachial index below 0.8, uncontrolled cardiac failure or renal insufficiency, pregnancy or lactation, and contraindications to ESWT or TECAR therapy including pacemaker or other implanted electronic devices. Patients receiving concurrent lymphedema treatment or those who had received intensive treatment within the preceding 3 months were excluded to avoid confounding effects.

Sample size was estimated a priori based on a between-group comparison using one-way ANOVA to detect a clinically meaningful difference of 1.5 cm in limb circumference reduction between groups (SD 1.2 cm, α=0.05, power=80%), yielding a minimum of 13 participants per group. Allowing for 15% attrition, 15 participants per group were recruited (total n = 45). Although the primary analysis employed a two-way mixed ANOVA, the

sample size calculation based on between-group differences represents a conservative approach, as repeated-measures designs typically provide greater statistical power than between-group comparisons alone due to the reduction in error variance achieved by accounting for within-subject correlations.

Randomization and Blinding

Eligible participants were randomly allocated to one of three treatment groups in a 1:1:1 ratio: CDT alone, CDT combined with TECAR, or CDT combined with ESWT. Randomization was performed using computer-generated random numbers with block randomization to ensure balanced group allocation. Allocation concealment was maintained through sequentially numbered sealed opaque envelopes prepared by an investigator not involved in participant recruitment or assessment.

Due to the nature of the interventions, therapists delivering treatment could not be blinded to group allocation. However, outcome assessors performing circumference measurements, tonometry, and administering questionnaires were blinded to treatment assignment. Participants were instructed not to discuss their treatment with assessors. Statistical analyses were performed by an investigator blinded to group allocation until completion of primary analyses.

Interventions

All three groups received identical complex decongestive therapy protocols following International Society of Lymphology consensus guidelines [1]. CDT was delivered five sessions per week for 4 weeks (a total of 20 sessions), with each session lasting approximately 60 minutes. The treatment protocol included: skin care education and examination for signs of infection or skin breakdown; manual lymphatic drainage performed by certified lymphedema therapists using gentle, rhythmic circular movements to stimulate lymphatic flow, beginning proximally and progressing distally; multilayer compression bandaging using short-stretch bandages applied from toes to upper thigh bilaterally, worn continuously between sessions and removed only for bathing and subsequent treatment sessions; supervised therapeutic exercises performed while wearing compression

bandages, including ankle pumps, knee flexion-extension, hip movements, and walking to promote muscle pump function; and patient education regarding self-care, risk reduction, and home exercise programs.

The CDT+TECAR group received identical CDT protocols plus TECAR therapy delivered using a capacitive-resistive device operating at 448 kHz frequency. TECAR was applied bilaterally to both lower limbs for 20 minutes per limb (40 minutes total per session) immediately prior to manual lymphatic drainage. Treatment was delivered in capacitive mode for superficial tissues and resistive mode for deeper structures, with the applicator moved continuously in circular motions progressing from proximal to distal. Energy output was adjusted to produce gentle warmth without discomfort, maintained at comfortable thermal levels throughout treatment. TECAR sessions were delivered five times weekly, concurrent with CDT sessions throughout the 4-week intervention period.

The CDT+ESWT group received identical CDT protocols plus extracorporeal shock wave therapy delivered using a radial ESWT device. Treatment was applied bilaterally to both lower limbs, targeting areas of maximum tissue firmness and edema. Each limb received 2000 shocks at 0.10–0.15 mJ/mm² energy density and 8–10 Hz frequency, distributed across ankle, calf, and thigh regions. ESWT was delivered three times weekly (sessions 1, 3, and 5 of each week) for the 4-week intervention period, immediately prior to CDT. Treatment areas included medial and lateral aspects of the ankle, anterior and posterior calf, and anterior and posterior thigh bilaterally.

Following completion of the 4-week intensive phase, all participants received standardized education regarding self-care and were fitted for custom compression garments to maintain treatment gains. Participants were instructed to wear compression stockings daily and perform self-manual lymphatic drainage. Compression bandaging was discontinued after the intensive phase.

Outcome Measures

All outcome assessments were performed at three time points: baseline (T0, prior to treatment initiation), 4 weeks (T1, immediately following completion of the 4-week intensive phase), and 8 weeks (T2, four weeks after cessation of intensive treatment).

Primary Outcome: The primary outcome was the change in limb circumference measured at standardized anatomical landmarks bilaterally. Measurements were obtained with participants in the supine position after 10 minutes of rest, using a flexible non-stretch tape measure. Circumferences were recorded at the following sites on both lower limbs: ankle (10 cm proximal to lateral malleolus), calf (widest circumference of gastrocnemius), knee (at mid-patella), mid-thigh (20 cm proximal to superior pole of patella), and upper-thigh (10 cm distal to inguinal crease). All measurements were performed by the same trained assessor, blinded to treatment allocation, with the average of two measurements recorded for each site. The assessor underwent reliability training, achieving an intraclass correlation coefficient ≥ 0.95 for all measurement sites.

Secondary Outcomes: Lymphedema-specific quality of life was assessed using the Lymphedema Quality of Life Questionnaire (LYMQOL) for the lower limb [19]. This validated instrument comprises 28 items across four domains: Function, Appearance, Symptoms, and Mood, plus an overall quality of life item. Each item is scored on a 4-point scale (1 = not at all to 4 = a lot), with domain scores calculated by summing items and dividing by the number of questions answered. Higher scores indicate poorer quality of life. For analysis, scores were converted to a 1–10 scale, where lower values represent a better quality of life. The LYMQOL has demonstrated good internal consistency and test–retest reliability for lower limb lymphedema [20].

Pain intensity was measured using a 10 cm Visual Analog Scale anchored at 0 (no pain) and 10 (worst imaginable pain). Participants marked their current lower limb pain level on the horizontal line, with distance from zero measured in centimeters to generate the pain score.

Tissue stiffness was quantified using tonometry at four sites bilaterally: left calf, right calf, left thigh, and right thigh. Tonometry was performed using a validated tissue tonometer device with standardized weight application. Measurements were taken at the point of maximum tissue firmness within each region, identified through palpation. The tonometer was applied perpendicular to the skin surface, and three measurements were obtained at each site with the median value recorded. Higher tonometry values indicate greater tissue stiffness. All tonometry measurements were performed by the same blinded assessor who underwent standardized training.

Adverse events were systematically recorded throughout the study period, with participants specifically queried about skin reactions, pain, discomfort, or any other symptoms at each treatment session and assessment visit.

Statistical Analysis

Data were analyzed using SPSS version 25 statistical software. Descriptive statistics included means and standard deviations for continuous variables and frequencies with percentages for categorical variables. Baseline characteristics were compared across the three groups using one-way analysis of variance (ANOVA) for continuous variables and chi-square tests for categorical variables.

The primary analysis employed a two-way mixed-design ANOVA (Group × Time) to evaluate treatment effects. The between-subjects factor was treatment group (CDT, CDT+TECAR, CDT+ESWT) and the within-subjects factor was time (baseline T0, 4 weeks T1, 8 weeks T2). This approach appropriately accounts for the repeated-measures structure, correlated observations, and enables direct testing of the Group × Time interaction effect, which indicates whether treatment groups differ in their trajectories of change over time.

Assumption testing included the Shapiro-Wilk test for normality of residuals, Levene's test for homogeneity of variances, and assessment of sphericity using the Greenhouse-Geisser epsilon. Where the sphericity assumption was violated ($\varepsilon < 0.75$), Greenhouse-Geisser corrected degrees of freedom and p-values were reported. Normality was confirmed for 97.2% of all group-by-time distributions (Shapiro-Wilk $p > 0.05$).

Significant Group × Time interactions were followed by Bonferroni-adjusted post-hoc pairwise comparisons between treatment groups at each time point using independent-samples t-tests. Three pairwise comparisons were conducted at each time point: CDT versus CDT+TECAR (p1), CDT versus CDT+ESWT (p2), and CDT+TECAR versus CDT+ESWT (p3).

Effect sizes were reported as partial eta squared (ηp^2) for mixed ANOVA effects, interpreted as small (0.01), medium (0.06), and large (≥0.14), and as Cohen's d for between-group pairwise comparisons, interpreted as small (0.2), medium (0.5), and large (≥0.8). The 95% confidence intervals (CIs) were calculated for group means and mean differences between groups. Statistical significance was set at $p < 0.05$ for all analyses. All analyses

followed intention-to-treat principles, with all randomized participants included in the analysis groups to which they were assigned.

Results

Participant Characteristics

A total of 62 patients were assessed for eligibility, of whom 17 were excluded (9 did not meet inclusion criteria, 5 declined to participate, and 3 were excluded for other reasons). The remaining 45 patients with bilateral lower limb lymphedema secondary to severe obesity were randomized between 25 October 2025 and 6 February 2026 (Figure 5, CONSORT flow diagram). All participants completed the 4-week intervention period and attended the 8-week follow-up assessment, with no dropouts or loss to follow-up.

The baseline demographic and clinical characteristics of participants are summarized in Table 1. The three treatment groups were comparable at baseline with respect to age, gender, body mass index, height, and weight ($p > 0.05$ for all comparisons). Similarly, no significant differences were observed between groups in baseline circumference measurements, LYMQOL scores, VAS pain, or tissue stiffness at all measurement sites ($p > 0.05$ for all comparisons).

Primary Outcome: Limb Circumference Reduction

Two-way mixed ANOVA revealed significant Group × Time interaction effects for all limb circumference measurements, indicating that treatment groups differed significantly in their patterns of change over time. For left ankle circumference, the interaction effect was $F(4, 84) = 464.06$, $p < 0.001$, $\eta p^2 = 0.957$ (large effect). Similar large interaction effects were observed at all other anatomical sites, with ηp^2 values ranging from 0.949 (left mid-thigh) to 0.989 (right calf) (Table 2).

At 4 weeks post-treatment, the mean reductions in left ankle circumference from baseline were −2.82 cm (95% CI: −2.88, −2.76) in the CDT group, −3.92 cm (95% CI: −3.99, −3.85) in the CDT+TECAR group, and −4.51 cm (95% CI: −4.60, −4.43) in the CDT+ESWT group. Post-hoc pairwise comparisons confirmed that both the CDT+TECAR and CDT+ESWT groups achieved significantly greater circumference reductions compared to the

CDT-only group at all anatomical points ($p < 0.001$). Between-group effect sizes were large: CDT versus CDT+TECAR, Cohen's d = 1.37; CDT versus CDT+ESWT, d = 1.83 for left ankle circumference at T1.

Furthermore, the CDT+ESWT group demonstrated superior outcomes compared to the CDT+TECAR group at most measurement sites ($p < 0.05$), with moderate-to-large between-group effect sizes (d = 0.53 to 1.46 at T1). The improvements were sustained at the 8-week follow-up assessment, with the CDT+ESWT group continuing to show the greatest circumference reductions (Table 2, Figures 1 and 2).

Clinical significance: While there is no universally established MCID for limb circumference in lymphedema, a reduction of ≥2 cm has been proposed as clinically meaningful based on prior literature. All three groups exceeded this threshold at all measurement sites, with the CDT+ESWT group achieving mean reductions of 3.4–11.7 cm depending on the anatomical site, substantially exceeding the proposed MCID. The magnitude of between-group differences (1.0–3.6 cm favoring CDT+ESWT over CDT alone) suggests these differences are not only statistically significant but also clinically relevant for functional improvement and compression garment fitting.

Secondary Outcomes

Quality of Life (LYMQOL): A significant Group × Time interaction was observed for all LYMQOL domains ($p < 0.001$ for all; Table 3, Figure 3). The interaction effect sizes were very large ($\eta p^2 = 0.991–0.998$). At 4 weeks, the mean change in overall quality of life score was −1.8 ± 0.2 in CDT, −2.2 ± 0.2 in CDT+TECAR, and −2.5 ± 0.2 in CDT+ESWT. The CDT+ESWT group achieved significantly greater improvements than both CDT (d = 7.29, $p < 0.001$) and CDT+TECAR (d = 3.25, $p < 0.05$) across all domains. These improvements were sustained at 8 weeks with slight deterioration. The MCID for LYMQOL has been estimated at approximately 1.0 point; all groups exceeded this threshold, with CDT+ESWT achieving the largest clinically meaningful gains.

Pain Intensity (VAS): The Group × Time interaction for VAS pain was significant ($F(4, 84) = 7864.25$, $p < 0.001$, $\eta p^2 = 0.997$). The mean reduction in VAS scores at 4 weeks was −2.5 ± 0.3 in CDT, −2.9 ± 0.3 in CDT+TECAR, and −3.3 ± 0.3 in CDT+ESWT. CDT+ESWT demonstrated significantly greater pain reduction compared to both CDT (mean difference = 0.83, 95% CI: 0.66–1.01, d = 3.54) and CDT+TECAR (mean

difference = 0.45, 95% CI: 0.28–0.61, d = 2.05). The established MCID for VAS is approximately 1.3–2.0 cm on a 10-cm scale; all groups exceeded this clinically important threshold (Table 4, Figure 4). At 8-week follow-up, pain scores showed slight increases but remained significantly improved from baseline.

Tissue Stiffness (Tonometry): Significant Group × Time interactions were observed for tissue stiffness at all measurement sites ($p < 0.001$; $\eta p^2 = 0.969–0.996$; Table 4, Figure 4). The mean reduction in left calf tissue stiffness at 4 weeks was −4.5 ± 0.4 units in CDT, −5.9 ± 0.4 units in CDT+TECAR, and −6.9 ± 0.4 units in CDT+ESWT. CDT+ESWT achieved significantly greater reductions compared to CDT ($d = 2.68$, $p < 0.001$) and CDT+TECAR ($d = 1.24$, $p < 0.01$) at all sites. Improvements were sustained at 8 weeks with modest increases in stiffness.

Adverse Events: No serious adverse events were reported in any treatment group. Minor adverse events included temporary skin redness (2 patients in CDT+TECAR, 1 in CDT+ESWT) and transient discomfort during sessions (3 in CDT, 2 in CDT+TECAR, 1 in CDT+ESWT). All adverse events resolved spontaneously without requiring treatment discontinuation.

Discussion

This randomized controlled trial demonstrated that both transfer energy capacitive and resistive therapy (TECAR) and extracorporeal shock wave therapy (ESWT) significantly enhanced the effectiveness of complex decongestive therapy (CDT) in severely obese patients with bilateral lower-limb lymphedema. All groups achieved significant reductions in limb circumference, pain intensity, tissue stiffness, and improvements in quality of life; however, the significant Group × Time interactions ($\eta p^2 = 0.949–0.998$) confirmed that adjunctive therapies produced differentially superior outcomes compared to CDT alone, with ESWT showing the most pronounced benefits across all measured outcomes.

According to international consensus guidelines, complex decongestive therapy remains the cornerstone of lymphedema management. However, its effectiveness may be limited in advanced stages of the disease and in patients with obesity. These challenges emphasize the need for adjunctive therapeutic modalities to enhance

clinical outcomes and support long-term disease control [21]. The findings align with previous reports that CDT remains the cornerstone of lymphedema management across etiologies [6]. Nevertheless, limitations in obesity-related lymphedema have been documented, including reduced responsiveness and recurrence of limb volume within one year [7,8]. The present results confirm that adjunctive modalities can overcome some of these limitations.

TECAR therapy, through radiofrequency-induced vasodilation and improved microcirculation [10,11], facilitated greater reductions in limb circumference and tissue stiffness compared to CDT alone. The mechanism of TECAR involves delivery of radiofrequency energy at 448 kHz, which induces endogenous tissue heating through both capacitive (superficial) and resistive (deep tissue) modes. Capacitive mode generates heating predominantly in water-rich tissues such as muscles and the lymphatic vasculature, while resistive mode targets tissues with higher impedance including fibrotic tissue and adipose deposits. This dual-mode heating promotes vasodilation, increases local blood flow, enhances cellular metabolic activity, and may facilitate the reabsorption of interstitial fluid by improving both venous and lymphatic return. In the context of obesity-related lymphedema, where adipose tissue compression of lymphatic vessels contributes to impaired drainage, the deep tissue heating effects of TECAR may be particularly relevant in reducing perilymphatic tissue resistance.

ESWT produced the largest improvements across all measured outcomes, consistent with prior evidence of its lymphangiogenic and anti-fibrotic effects [12–16]. The mechanistic advantage of ESWT in chronic lymphedema is likely multifactorial. At the molecular level, mechanical shockwaves upregulate vascular endothelial growth factor-C (VEGF-C) expression, which binds to VEGFR-3 receptors on lymphatic endothelial cells, stimulating lymphangiogenesis—the formation of new lymphatic vessels. This neolymphangiogenesis may partially restore lymphatic drainage capacity in regions where existing lymphatic channels have been damaged or compressed by excess adipose tissue. Additionally, ESWT modulates collagen turnover by upregulating matrix metalloproteinases (MMPs), particularly MMP-2 and MMP-9, which degrade excess extracellular matrix components, thereby reducing tissue fibrosis. This anti-fibrotic effect is particularly relevant in obesity-related lymphedema, where chronic inflammation mediated by adipokines (leptin, TNF-α, IL-6) perpetuates a cycle of

fibrosis, adipose deposition, and further lymphatic impairment. ESWT also stimulates nitric oxide production, promoting vasodilation and improving microvascular perfusion in affected tissues [22,23]. The combination of these mechanisms—lymphangiogenesis, fibrosis reduction, and improved microcirculation—provides a comprehensive biological rationale for ESWT's superior performance compared to both CDT alone and CDT+TECAR in this trial.

In the specific pathophysiological context of obesity-related lymphedema, excessive adipose tissue exerts mechanical compression on lymphatic vessels and impairs their contractile function. Adipose-derived inflammatory mediators further damage lymphatic endothelium and promote subendothelial fibrosis. The finding that both adjunctive therapies improved tissue stiffness, as measured by tonometry, suggests that targeting the fibrotic component of obesity-related lymphedema may be essential for optimizing treatment outcomes. The larger effect sizes observed for ESWT across tissue stiffness measurements support the hypothesis that its anti-fibrotic properties confer a distinct therapeutic advantage in this population. It should be noted, however, that some of the Cohen’s d values reported in this study are notably large, which may be partially attributable to the small within-group variability observed across several outcome measures and the relatively small sample size (n = 15 per group). Accordingly, the mean differences and their 95% confidence intervals should be considered the more clinically interpretable measures of treatment effect, while the d values should be interpreted with appropriate caution.

Importantly, this study extends existing literature by focusing on obesity-related bilateral lower-limb lymphedema, a population underrepresented in prior trials that predominantly examined breast cancer-related upper-limb disease [14,15]. The demonstration of efficacy in severely obese patients with large effect sizes (Cohen's d > 0.8 for all CDT vs CDT+ESWT comparisons) addresses a critical gap and highlights the potential of ESWT and TECAR as adjuncts in this challenging clinical context.

Clinical implications include the integration of ESWT into CDT protocols, particularly for patients with advanced fibrosis, where its anti-fibrotic properties may yield sustained benefit. TECAR remains a valuable option,

especially where rapid volume reduction is desired. Both modalities were well tolerated, with only minor, transient adverse events reported, underscoring their safety in this population.

Limitations

Several limitations warrant consideration and should be acknowledged for methodological transparency. First, the sample size was modest (n = 15 per group), and although powered for the primary outcome of circumference reduction, larger multicenter studies are needed to confirm generalizability and detect smaller between-group differences with greater precision. Second, the follow-up period was limited to 8 weeks (4 weeks post-intervention), preventing assessment of long-term durability of treatment effects; given that obesity-related lymphedema is a chronic progressive condition, studies with 6–12 month follow-up are essential to determine whether the observed benefits are maintained. Third, the study population comprised only female patients, restricting extrapolation to males with obesity-related lymphedema.

Fourth, the absence of a sham control group for TECAR and ESWT means that specific treatment effects cannot be fully separated from non-specific effects such as therapist attention and patient expectation. Fifth, therapists delivering the interventions were not blinded to treatment allocation, which may introduce performance bias, although outcome assessors remained blinded. Sixth, no objective imaging modalities such as lymphoscintigraphy or indocyanine green lymphography were employed to assess lymphatic function directly; the reliance on circumference measurements and tonometry, while clinically relevant, does not capture the underlying lymphatic structural and functional changes. Seventh, tissue fibrosis was assessed indirectly via tonometry rather than by elastography or histological analysis, limiting the depth of conclusions regarding fibrosis remodeling. Eighth, this was a single-center study, which may limit the generalizability of findings to other clinical settings and populations. Ninth, the trial was registered through an institutional ethics committee registry rather than an international public registry (e.g., ClinicalTrials.gov), and retrospective registration on a public platform is currently underway; this may be considered a limitation regarding registration transparency.

Future research should evaluate longer-term outcomes, include male participants, incorporate sham control arms, and explore combined or sequential use of TECAR and ESWT. Objective imaging modalities such as lymphoscintigraphy, indocyanine green lymphography, or shear wave elastography could provide deeper insights into tissue remodeling, lymphatic function, and fibrosis resolution. Dose-response studies to optimize ESWT parameters in this population are also warranted.

Conclusion

Adjunctive TECAR and ESWT significantly improved outcomes beyond CDT alone in severely obese patients with bilateral lower-limb lymphedema, with large effect sizes across all measured outcomes. ESWT demonstrated the greatest benefits, consistent with its lymphangiogenic and anti-fibrotic mechanisms. The significant Group × Time interactions and clinically meaningful differences support the incorporation of adjunctive therapies, particularly ESWT, into standard CDT protocols to optimize management of obesity-related lymphedema. Larger multicenter trials with longer follow-up and objective imaging are needed to confirm durability and broaden applicability.

Ethics Approval

The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Scientific Research Ethics Committee, Al Salam University. All participants provided written informed consent before enrollment. The trial was registered at Al Salam University under the identification number No: SREC.PT.SUE (19)1025, on 25.10.2025.

Informed Consent

Written informed consent was obtained from all participants before the start of the study.

Consent for Publication

All authors have reviewed the final version of the manuscript and agree to its submission. We confirm that the work is original, has neither been published elsewhere nor under consideration for publication in any other journal.

Availability of Data

The datasets used during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare no competing interests.

Funding

The research was funded by the Applied Science Private University, Amman, Jordan, Grant number: DRGS/2025-13.

Authors' Contributions

Mostafa A Abdelhameed, Mohamed I. Mabrouk, Rama Alrawajfeh, Aseel Aburub, and Sami Elmahgoub contributed to the study design, data collection, data analysis, methodology development, literature review, and drafting of the manuscript. Shymaa M. Ali and Pongrác Ács contributed to methodology development, literature

review, and statistical analysis, and provided critical revisions to the manuscript. Bence Cselik contributed to the study design and methodology, supervised the study, guided the conceptual framework, and provided important feedback throughout the research process. All authors read and approved the final version of the manuscript.

Acknowledgements

The authors would like to acknowledge the financial support provided for this research by the Applied Science Private University. We also acknowledge the assistance of the Rehabilitation Department and Physical Medicine Unit at Modawah Physical Therapy and Rehabilitation Center, which helped with the study for access to facilities.

Trial Registration Transparency Statement

This trial was registered with the Scientific Research Ethics Committee (SREC) at Al Salam University, Faculty of Physical Therapy, under the identification number SREC.PT.SUE (19)1025, on 25 October 2025. Ethical approval and registration were obtained prior to the commencement of data collection. The authors acknowledge that this registration was conducted through an institutional ethics committee registry rather than an international public clinical trial registry (e.g., ClinicalTrials.gov, ISRCTN). To enhance transparency and public accessibility, the trial is being retrospectively registered on ClinicalTrials.gov, and the full protocol and registration details will be made publicly available upon completion of this process.

List of Abbreviations

CDT: Complex Decongestive Therapy; ESWT: Extracorporeal Shock Wave Therapy; TECAR: Transfer Energy Capacitive and Resistive Therapy; LYMQOL: Lymphedema Quality of Life Questionnaire; VAS: Visual Analogue Scale; BMI: Body Mass Index; RCT: Randomized Controlled Trial; VEGF-C: Vascular Endothelial Growth Factor C; VEGFR-3: Vascular Endothelial Growth Factor Receptor 3; MMP: Matrix Metalloproteinase; MCID: Minimal Clinically Important Difference; CI: Confidence Interval; ANOVA: Analysis of Variance; CONSORT: Consolidated Standards of Reporting Trials.

References

1. Executive Committee of the International Society of Lymphology. The diagnosis and treatment of peripheral lymphedema: 2020 consensus document of the International Society of Lymphology. Lymphology. 2020;53(1):3-19.

2. Greene AK, Grant FD, Slavin SA. Lower-extremity lymphedema and elevated body-mass index. N Engl J Med. 2012;366(22):2136-2137.

3. Duyur Çakıt B, Pervane Vural S, Genç H. Complex decongestive therapy in breast cancer-related lymphedema: does obesity affect the outcome negatively? Lymphat Res Biol. 2019;17(1):45-50.

4. Greene AK, Sudduth CL. Obesity-induced lymphedema. Cold Spring Harb Perspect Med. 2022;12(6):a041176.

5. Greene AK, Grant FD, Maclellan RA. Obesity-induced lymphedema: clinical and lymphoscintigraphic features. Plast Reconstr Surg Glob Open. 2015;3(6):e426.

6. Lasinski BB, McKillip Thrift K, Squire D, et al. A systematic review of the evidence for complete decongestive therapy in the treatment of lymphedema from 2004 to 2011. PM R. 2012;4(8):580-601.

7. Yaman A, Borman P, Karakuzu Güngör Ö, et al. The impact of obesity on the outcomes of complex decongestive therapy among patients with breast cancer-related lymphedema. Turk J Phys Med Rehabil. 2025;71(1):64-73.

8. Borman P, Yaman A, Yasrebi S, İnanlı AP, Arıkan Dönmez A. Combined complete decongestive therapy reduces volume and improves quality of life and functional status in patients with breast cancer-related lymphedema. Clin Breast Cancer. 2022;22(3):e270-e277.

9. Mehrara BJ, Greene AK. Lymphedema and obesity: is there a link? Plast Reconstr Surg. 2014;134(1):154e-160e.

10. Hernandez-Bule ML, Toledano Macías E, Martínez Pascual MA, et al. Does the application of Tecar therapy affect temperature and perfusion of skin and muscle microcirculation? A pilot feasibility study on healthy subjects. J Clin Med. 2019;8(10):1645.

11. Cau N, Cimolin V, Aspesi V, et al. Preliminary evidence of effectiveness of TECAR in lymphedema. Lymphology. 2019;52(1):35-43.

12. Kubo M, Li TS, Kamota T, et al. Extracorporeal shock wave therapy ameliorates secondary lymphedema by promoting lymphangiogenesis. J Vasc Surg. 2010;52(2):429-434.

13. Serizawa F, Ito K, Matsubara M, et al. Extracorporeal shock wave therapy induces therapeutic lymphangiogenesis in a rat model of secondary lymphoedema. Eur J Vasc Endovasc Surg. 2011;42(2):254-260.

14. Lee JH, Kim SB, Lee KW, Ha WW. Long-term effects of extracorporeal shock wave therapy on breast cancer-related lymphedema. J Clin Med. 2022;11(22):6747.

15. Tsai YL, I TJ, Chuang YC, Cheng YY, Lee YC. Extracorporeal shock wave therapy combined with complex decongestive therapy in patients with breast cancer-related lymphedema: a systematic review and meta-analysis. J Clin Med. 2021;10(24):5970.

16. Lee KW, Kim SB, Lee JH, Kim YS. Effects of extracorporeal shockwave therapy on improvements in lymphedema, quality of life, and fibrous tissue in breast cancer-related lymphedema. Ann Rehabil Med. 2020;44(5):386-392.

17. Greene AK, Grant FD, Slavin SA. Obesity-induced lymphedema: clinical and lymphoscintigraphic features. Plast Reconstr Surg. 2015;135(6):1715-1719.

18. Rockson SG. Lymphedema. N Engl J Med. 2018;379(20):1937-1944.

19. Keeley V, Crooks S, Locke J, Veigas D, Riches K, Hilliam R. A quality of life measure for limb lymphoedema (LYMQOL). J Lymphoedema. 2010;5(1):26-37.

20. Nuwayhid R, Mardian Y, Ure C, et al. Translation, cross-cultural adaptation and validation of the LYMQOL in German-speaking patients with lymphedema of the lower limbs. Healthcare (Basel). 2024;12(3):409.

21. International Society of Lymphology. The diagnosis and treatment of peripheral lymphedema: 2016 consensus document. Lymphology. 2016;49(4):170-184.

22. Wang CJ, Wu RW, Yang YJ. Treatment of diabetic foot ulcers: a comparative study of extracorporeal shock wave therapy and hyperbaric oxygen therapy. Diabetes Res Clin Pract. 2011;92(2):187-193.

23. Mabrouk MI, Badr NM, Taha MM, El-Shiwi AM, Abdelaal AM, Ali SM, Abd El-Hamed A. Effect of extracorporeal shock wave therapy on skin blood perfusion in patients with diabetic foot: a randomized controlled trial. Int J Adv Res. 2015;3(3):144-154.

Tables

Table 1: Baseline Demographic and Clinical Characteristics of Participants

Variable	CDT (n=15)	CDT+TECAR (n=15)	CDT+ESWT (n=15)	p-value
Demographics				
Age (years)	57.1 ± 3.8 [55.0, 59.1]	56.8 ± 3.0 [55.1, 58.5]	57.2 ± 2.7 [55.7, 58.7]	0.941
BMI (kg/m²)	44.3 ± 1.8 [43.3, 45.3]	44.1 ± 1.5 [43.3, 45.0]	44.4 ± 1.4 [43.6, 45.1]	0.937
Height (cm)	159.6 ± 2.1 [158.4, 160.8]	159.5 ± 1.7 [158.6, 160.4]	159.7 ± 1.5 [158.9, 160.6]	0.928
Weight (kg)	112.9 ± 7.7 [108.7, 117.2]	112.4 ± 6.2 [109.0, 115.8]	113.2 ± 5.8 [110.0, 116.4]	0.947
Gender (Female), n (%)	15 (100%)	15 (100%)	15 (100%)	—
Baseline Circumference — Left Limb (cm)				
Ankle	28.2 ± 1.1 [27.6, 28.8]	28.1 ± 0.9 [27.6, 28.6]	28.2 ± 0.9 [27.7, 28.7]	0.883
Calf	45.4 ± 1.9 [44.4, 46.5]	45.4 ± 1.5 [44.5, 46.2]	45.7 ± 1.5 [44.8, 46.5]	0.875
Knee	52.1 ± 2.1 [50.9, 53.2]	52.0 ± 1.7 [51.1, 53.0]	52.3 ± 1.6 [51.4, 53.3]	0.881
Mid-thigh	68.4 ± 2.4 [67.1, 69.7]	68.2 ± 1.9 [67.1, 69.2]	68.5 ± 1.9 [67.5, 69.6]	0.898
Upper-thigh	72.6 ± 2.5 [71.2, 74.0]	72.5 ± 2.0 [71.4, 73.6]	72.8 ± 2.0 [71.7, 74.0]	0.892
Baseline Circumference — Right Limb (cm)				
Ankle	28.2 ± 0.6 [27.9, 28.5]	28.3 ± 0.6 [28.0, 28.7]	28.3 ± 0.5 [28.0, 28.6]	0.779
Calf	45.6 ± 0.9 [45.2, 46.1]	45.9 ± 0.8 [45.5, 46.4]	45.9 ± 0.7 [45.5, 46.3]	0.554
Knee	52.6 ± 1.0 [52.1, 53.2]	53.0 ± 1.0 [52.4, 53.6]	52.9 ± 0.9 [52.4, 53.4]	0.619

Mid-thigh	68.7 ± 1.4 [68.0, 69.5]	69.2 ± 1.3 [68.5, 70.0]	69.1 ± 1.2 [68.4, 69.8]	0.584
Upper-thigh	73.1 ± 1.5 [72.2, 73.9]	73.6 ± 1.4 [72.8, 74.4]	73.5 ± 1.3 [72.7, 74.2]	0.555
Baseline LYMQOL Scores (1–10)				
Function	6.6 ± 0.3 [6.4, 6.8]	6.7 ± 0.3 [6.6, 6.9]	6.7 ± 0.3 [6.5, 6.8]	0.598
Appearance	6.9 ± 0.2 [6.8, 7.0]	6.8 ± 0.2 [6.7, 6.9]	6.9 ± 0.2 [6.8, 7.0]	0.587
Symptoms	6.3 ± 0.3 [6.1, 6.5]	6.4 ± 0.3 [6.2, 6.5]	6.3 ± 0.3 [6.2, 6.5]	0.796
Mood	6.1 ± 0.2 [6.0, 6.2]	6.1 ± 0.1 [6.0, 6.2]	6.1 ± 0.2 [6.1, 6.2]	0.648
Overall QOL	6.5 ± 0.1 [6.4, 6.6]	6.5 ± 0.1 [6.5, 6.6]	6.5 ± 0.1 [6.5, 6.6]	0.720
Baseline Pain and Tissue Stiffness				
VAS Pain (0-10)	6.1 ± 0.3 [6.0, 6.2]	6.2 ± 0.2 [6.1, 6.3]	6.2 ± 0.2 [6.1, 6.3]	0.395
Stiffness Calf Left	34.7 ± 1.4 [33.9, 35.5]	34.5 ± 1.3 [33.7, 35.2]	34.7 ± 1.3 [34.0, 35.5]	0.833
Stiffness Calf Right	34.8 ± 0.5 [34.5, 35.0]	34.8 ± 0.4 [34.5, 35.0]	34.8 ± 0.4 [34.6, 35.0]	0.990
Stiffness Thigh Left	31.5 ± 1.3 [30.8, 32.2]	31.4 ± 1.2 [30.7, 32.0]	31.6 ± 1.2 [30.9, 32.3]	0.869
Stiffness Thigh Right	31.6 ± 0.6 [31.3, 32.0]	31.6 ± 0.6 [31.3, 31.9]	31.6 ± 0.5 [31.4, 31.9]	0.943

Data presented as Mean ± SD [95% CI] or n (%).

Statistical test: One-way ANOVA for continuous variables; Chi-square test for categorical variables.

No significant between-group differences at baseline ($p > 0.05$ for all comparisons).

Table 2: Primary Outcome — Limb Circumference Comparison Between Groups

Variable	Time	CDT (n=15)	CDT+TECAR (n=15)	CDT+ESWT (n=15)	p1 (d)	p2 (d)	p3 (d)
Left Ankle	T0	28.2 ± 1.1 [27.6, 28.8]	28.1 ± 0.9 [27.6, 28.6]	28.2 ± 0.9 [27.7, 28.7]	—	—	—
Left Ankle	T1	25.4 ± 1.0 [24.8, 26.0]	24.1 ± 0.8 [23.7, 24.6]	23.7 ± 0.8 [23.3, 24.1]	<0.001 (1.37)	<0.001 (1.83)	0.145 (0.55)
Left Ankle	T2	24.8 ± 1.0 [24.3, 25.4]	23.9 ± 0.8 [23.5, 24.4]	23.5 ± 0.8 [23.1, 23.9]	0.011 (1.0)	<0.001 (1.47)	0.145 (0.55)
Left Calf	T0	45.4 ± 1.9 [44.4, 46.5]	45.4 ± 1.5 [44.5, 46.2]	45.7 ± 1.5 [44.8, 46.5]	—	—	—
Left Calf	T1	40.9 ± 1.7 [39.9, 41.9]	39.0 ± 1.3 [38.3, 39.8]	38.3 ± 1.2 [37.7, 39.0]	0.003 (1.21)	<0.001 (1.69)	0.156 (0.53)
Left Calf	T2	40.0 ± 1.7 [39.1, 41.0]	38.6 ± 1.3 [37.9, 39.3]	37.9 ± 1.2 [37.3, 38.6]	0.016 (0.94)	<0.001 (1.39)	0.178 (0.5)
Left Knee	T0	52.1 ± 2.1 [50.9, 53.2]	52.0 ± 1.7 [51.1, 53.0]	52.3 ± 1.6 [51.4, 53.3]	—	—	—
Left Knee	T1	46.9 ± 1.9 [45.8, 47.9]	44.8 ± 1.4 [44.0, 45.6]	44.0 ± 1.4 [43.2, 44.7]	0.002 (1.27)	<0.001 (1.77)	0.128 (0.57)
Left Knee	T2	45.9 ± 1.8 [44.8, 46.9]	44.2 ± 1.4 [43.5, 45.0]	43.5 ± 1.4 [42.8, 44.3]	0.010 (1.0)	<0.001 (1.43)	0.183 (0.5)
Left Mid-thigh	T0	68.4 ± 2.4 [67.1, 69.7]	68.2 ± 1.9 [67.1, 69.2]	68.5 ± 1.9 [67.5, 69.6]	—	—	—

Left Mid-thigh	T1	61.5 ± 2.1 [60.4, 62.7]	58.6 ± 1.6 [57.7, 59.5]	57.5 ± 1.5 [56.7, 58.3]	<0.001 (1.54)	<0.001 (2.21)	0.059 (0.72)
Left Mid-thigh	T2	60.2 ± 2.1 [59.1, 61.4]	58.0 ± 1.6 [57.1, 58.8]	56.9 ± 1.5 [56.1, 57.7]	0.002 (1.21)	<0.001 (1.82)	0.072 (0.68)
Left Upper-thigh	T0	72.6 ± 2.5 [71.2, 74.0]	72.5 ± 2.0 [71.4, 73.6]	72.8 ± 2.0 [71.7, 74.0]	—	—	—
Left Upper-thigh	T1	65.4 ± 2.3 [64.1, 66.6]	62.3 ± 1.7 [61.4, 63.3]	61.2 ± 1.7 [60.3, 62.1]	<0.001 (1.53)	<0.001 (2.1)	0.080 (0.66)
Left Upper-thigh	T2	64.0 ± 2.2 [62.7, 65.2]	61.6 ± 1.7 [60.7, 62.6]	60.6 ± 1.7 [59.7, 61.5]	0.003 (1.17)	<0.001 (1.71)	0.097 (0.63)
Right Ankle	T0	28.2 ± 0.6 [27.9, 28.5]	28.3 ± 0.6 [28.0, 28.7]	28.3 ± 0.5 [28.0, 28.6]	—	—	—
Right Ankle	T1	25.4 ± 0.5 [25.1, 25.7]	24.4 ± 0.5 [24.1, 24.6]	23.8 ± 0.4 [23.5, 24.0]	<0.001 (2.07)	<0.001 (3.43)	0.001 (1.31)
Right Ankle	T2	24.8 ± 0.5 [24.5, 25.1]	24.2 ± 0.5 [23.9, 24.4]	23.6 ± 0.4 [23.3, 23.8]	0.001 (1.29)	<0.001 (2.64)	0.001 (1.31)
Right Calf	T0	45.6 ± 0.9 [45.2, 46.1]	45.9 ± 0.8 [45.5, 46.4]	45.9 ± 0.7 [45.5, 46.3]	—	—	—
Right Calf	T1	41.1 ± 0.8 [40.6, 41.5]	39.5 ± 0.7 [39.1, 39.9]	38.5 ± 0.6 [38.2, 38.9]	<0.001 (2.1)	<0.001 (3.63)	<0.001 (1.46)
Right Calf	T2	40.2 ± 0.8 [39.8, 40.6]	39.1 ± 0.7 [38.7, 39.5]	38.1 ± 0.6 [37.8, 38.5]	<0.001 (1.52)	<0.001 (2.95)	<0.001 (1.4)

Right Knee	T0	52.6 ± 1.0 [52.1, 53.2]	53.0 ± 1.0 [52.4, 53.6]	52.9 ± 0.9 [52.4, 53.4]	—	—	—
Right Knee	T1	47.4 ± 1.0 [46.8, 47.9]	45.6 ± 0.9 [45.1, 46.1]	44.4 ± 0.8 [44.0, 44.9]	<0.001 (1.93)	<0.001 (3.37)	<0.001 (1.35)
Right Knee	T2	46.4 ± 0.9 [45.8, 46.9]	45.0 ± 0.9 [44.5, 45.5]	44.0 ± 0.8 [43.6, 44.5]	<0.001 (1.42)	<0.001 (2.68)	0.003 (1.21)
Right Mid-thigh	T0	68.7 ± 1.4 [68.0, 69.5]	69.2 ± 1.3 [68.5, 70.0]	69.1 ± 1.2 [68.4, 69.8]	—	—	—
Right Mid-thigh	T1	61.9 ± 1.3 [61.2, 62.6]	59.5 ± 1.2 [58.9, 60.2]	58.1 ± 1.0 [57.5, 58.6]	<0.001 (1.92)	<0.001 (3.27)	<0.001 (1.35)
Right Mid-thigh	T2	60.5 ± 1.2 [59.9, 61.2]	58.9 ± 1.2 [58.3, 59.6]	57.5 ± 1.0 [57.0, 58.1]	0.001 (1.34)	<0.001 (2.69)	0.001 (1.32)
Right Upper-thigh	T0	73.1 ± 1.5 [72.2, 73.9]	73.6 ± 1.4 [72.8, 74.4]	73.5 ± 1.3 [72.7, 74.2]	—	—	—
Right Upper-thigh	T1	65.8 ± 1.3 [65.0, 66.5]	63.3 ± 1.2 [62.6, 64.0]	61.7 ± 1.1 [61.1, 62.3]	<0.001 (1.94)	<0.001 (3.35)	<0.001 (1.4)
Right Upper-thigh	T2	64.3 ± 1.3 [63.6, 65.1]	62.7 ± 1.2 [62.0, 63.4]	61.1 ± 1.1 [60.5, 61.7]	0.001 (1.31)	<0.001 (2.69)	<0.001 (1.36)

Data presented as Mean ± SD [95% CI].

Statistical test: Two-way mixed ANOVA (Group × Time) for overall effects; Bonferroni-adjusted independent t-tests for post-hoc pairwise comparisons.

p1: CDT vs CDT+TECAR; p2: CDT vs CDT+ESWT; p3: CDT+TECAR vs CDT+ESWT. d = Cohen's d.

All Group × Time interactions significant ($p < 0.001$). See Table 5 for full ANOVA results.

Table 3: Secondary Outcome — LYMQOL Scores Comparison Between Groups

Variable	Time	CDT (n=15)	CDT+TECAR (n=15)	CDT+ESWT (n=15)	p1 (d)	p2 (d)	p3 (d)
Function	T0	6.6 ± 0.3 [6.4, 6.8]	6.7 ± 0.3 [6.6, 6.9]	6.7 ± 0.3 [6.5, 6.8]	—	—	—
Function	T1	4.9 ± 0.3 [4.7, 5.1]	4.5 ± 0.3 [4.4, 4.7]	4.2 ± 0.3 [4.0, 4.3]	0.004 (1.13)	<0.001 (2.39)	0.002 (1.22)
Function	T2	5.1 ± 0.3 [4.9, 5.3]	4.6 ± 0.3 [4.5, 4.8]	4.3 ± 0.3 [4.1, 4.4]	<0.001 (1.44)	<0.001 (2.72)	0.002 (1.22)
Appearance	T0	6.9 ± 0.2 [6.8, 7.0]	6.8 ± 0.2 [6.7, 6.9]	6.9 ± 0.2 [6.8, 7.0]	—	—	—
Appearance	T1	5.2 ± 0.2 [5.1, 5.3]	4.6 ± 0.2 [4.5, 4.7]	4.4 ± 0.2 [4.3, 4.5]	<0.001 (2.81)	<0.001 (4.35)	0.001 (1.3)
Appearance	T2	5.4 ± 0.2 [5.3, 5.5]	4.7 ± 0.2 [4.6, 4.8]	4.5 ± 0.2 [4.4, 4.6]	<0.001 (3.3)	<0.001 (4.87)	0.001 (1.3)
Symptoms	T0	6.3 ± 0.3 [6.1, 6.5]	6.4 ± 0.3 [6.2, 6.5]	6.3 ± 0.3 [6.2, 6.5]	—	—	—
Symptoms	T1	4.6 ± 0.3 [4.4, 4.8]	4.2 ± 0.4 [4.0, 4.4]	3.8 ± 0.3 [3.7, 4.0]	0.004 (1.16)	<0.001 (2.38)	0.006 (1.09)
Symptoms	T2	4.8 ± 0.3 [4.6, 5.0]	4.3 ± 0.4 [4.1, 4.5]	3.9 ± 0.3 [3.8, 4.1]	<0.001 (1.45)	<0.001 (2.69)	0.006 (1.09)
Mood	T0	6.1 ± 0.2 [6.0, 6.2]	6.1 ± 0.1 [6.0, 6.2]	6.1 ± 0.2 [6.1, 6.2]	—	—	—
Mood	T1	4.4 ± 0.2 [4.3, 4.5]	3.9 ± 0.1 [3.8, 4.0]	3.6 ± 0.2 [3.6, 3.7]	<0.001 (3.11)	<0.001 (4.64)	<0.001 (1.91)
Mood	T2	4.6 ± 0.2 [4.5, 4.7]	4.0 ± 0.1 [3.9, 4.1]	3.7 ± 0.2 [3.7, 3.8]	<0.001 (3.73)	<0.001 (5.24)	<0.001 (1.91)

Overall QOL	T0	6.5 ± 0.1 [6.4, 6.6]	6.5 ± 0.1 [6.5, 6.6]	6.5 ± 0.1 [6.5, 6.6]	—	—	—
Overall QOL	T1	4.8 ± 0.1 [4.7, 4.9]	4.3 ± 0.1 [4.3, 4.4]	4.0 ± 0.1 [4.0, 4.1]	<0.001 (3.66)	<0.001 (7.29)	<0.001 (3.25)
Overall QOL	T2	5.0 ± 0.1 [4.9, 5.1]	4.4 ± 0.1 [4.4, 4.5]	4.1 ± 0.1 [4.1, 4.2]	<0.001 (4.65)	<0.001 (8.24)	<0.001 (3.34)

Data presented as Mean ± SD [95% CI]. LYMQOL scores range 1–10 (lower scores = better quality of life).

Statistical test: Two-way mixed ANOVA (Group × Time) for overall effects; Bonferroni-adjusted independent t-tests for post-hoc pairwise comparisons.

p1: CDT vs CDT+TECAR; p2: CDT vs CDT+ESWT; p3: CDT+TECAR vs CDT+ESWT. d = Cohen's d.

Table 4: Secondary Outcome — VAS Pain and Tissue Stiffness Comparison Between Groups

Variable	Time	CDT (n=15)	CDT+TECAR (n=15)	CDT+ESWT (n=15)	p1 (d)	p2 (d)	p3 (d)
VAS Pain	T0	6.1 ± 0.3 [6.0, 6.2]	6.2 ± 0.2 [6.1, 6.3]	6.2 ± 0.2 [6.1, 6.3]	—	—	—
VAS Pain	T1	3.6 ± 0.3 [3.5, 3.7]	3.2 ± 0.2 [3.1, 3.3]	2.8 ± 0.2 [2.7, 2.9]	<0.001 (1.59)	<0.001 (3.54)	<0.001 (2.05)
VAS Pain	T2	3.9 ± 0.3 [3.8, 4.0]	3.4 ± 0.2 [3.3, 3.5]	3.0 ± 0.2 [2.9, 3.1]	<0.001 (2.0)	<0.001 (3.96)	<0.001 (2.05)
Stiffness Left Calf	T0	34.7 ± 1.4 [33.9, 35.5]	34.5 ± 1.3 [33.7, 35.2]	34.7 ± 1.3 [34.0, 35.5]	—	—	—
Stiffness Left Calf	T1	30.2 ± 1.3 [29.5, 30.9]	28.5 ± 1.1 [27.8, 29.1]	27.1 ± 1.0 [26.5, 27.7]	<0.001 (1.48)	<0.001 (2.68)	0.002 (1.24)
Stiffness Left Calf	T2	30.7 ± 1.3 [30.0, 31.4]	28.8 ± 1.1 [28.1, 29.4]	27.4 ± 1.0 [26.8, 28.0]	<0.001 (1.65)	<0.001 (2.85)	0.002 (1.24)
Stiffness Right Calf	T0	34.8 ± 0.5 [34.5, 35.0]	34.8 ± 0.4 [34.5, 35.0]	34.8 ± 0.4 [34.6, 35.0]	—	—	—
Stiffness Right Calf	T1	30.3 ± 0.4 [30.0, 30.5]	28.7 ± 0.3 [28.5, 28.9]	27.2 ± 0.3 [27.0, 27.4]	<0.001 (4.09)	<0.001 (8.08)	<0.001 (4.49)
Stiffness Right Calf	T2	30.8 ± 0.4 [30.5, 31.0]	29.0 ± 0.3 [28.8, 29.2]	27.5 ± 0.3 [27.3, 27.7]	<0.001 (4.59)	<0.001 (8.6)	<0.001 (4.55)
Stiffness Left Thigh	T0	31.5 ± 1.3 [30.8, 32.2]	31.4 ± 1.2 [30.7, 32.0]	31.6 ± 1.2 [30.9, 32.3]	—	—	—

Stiffness Left Thigh	T1	27.4 ± 1.1 [26.8, 28.1]	25.9 ± 1.0 [25.4, 26.5]	24.7 ± 0.9 [24.2, 25.2]	<0.001 (1.43)	<0.001 (2.64)	0.001 (1.29)
Stiffness Left Thigh	T2	27.9 ± 1.1 [27.3, 28.6]	26.2 ± 1.0 [25.7, 26.8]	25.0 ± 0.9 [24.5, 25.5]	<0.001 (1.62)	<0.001 (2.84)	0.001 (1.29)
Stiffness Right Thigh	T0	31.6 ± 0.6 [31.3, 32.0]	31.6 ± 0.6 [31.3, 31.9]	31.6 ± 0.5 [31.4, 31.9]	—	—	—
Stiffness Right Thigh	T1	27.5 ± 0.5 [27.3, 27.8]	26.1 ± 0.5 [25.8, 26.3]	24.7 ± 0.4 [24.5, 24.9]	<0.001 (3.04)	<0.001 (6.54)	<0.001 (3.36)
Stiffness Right Thigh	T2	28.0 ± 0.5 [27.8, 28.3]	26.4 ± 0.5 [26.1, 26.6]	25.0 ± 0.4 [24.8, 25.2]	<0.001 (3.46)	<0.001 (7.0)	<0.001 (3.36)

Data presented as Mean ± SD [95% CI]. VAS Pain: 0 = no pain, 10 = worst pain. Tissue stiffness measured by tonometry (higher values = greater stiffness).

Statistical test: Two-way mixed ANOVA (Group × Time) for overall effects; Bonferroni-adjusted independent t-tests for post-hoc pairwise comparisons.

p1: CDT vs CDT+TECAR; p2: CDT vs CDT+ESWT; p3: CDT+TECAR vs CDT+ESWT. d = Cohen's d.

Table 5: Two-Way Mixed ANOVA Summary — Group, Time, and Group × Time Interaction Effects

Variable	Group F	Group p	Group ηp^2	Time F	Time p	Time ηp^2	G×T F	G×T p	G×T ηp^2
Left Ankle	4.89	0.012	0.189	34867.3	<0.001	0.999	464.06	<0.001	0.957
Left Calf	3.8	0.031	0.153	31330.72	<0.001	0.999	442.92	<0.001	0.955
Left Knee	4.16	0.022	0.165	37801.64	<0.001	0.999	522.79	<0.001	0.961
Left Mid-thigh	6.67	0.003	0.241	28142.22	<0.001	0.999	393.92	<0.001	0.949
Left Upper-thigh	6.16	0.005	0.227	51351.44	<0.001	0.999	700.58	<0.001	0.971
Right Ankle	12.66	<0.001	0.376	99864.63	<0.001	1.0	1339.66	<0.001	0.985
Right Calf	14.54	<0.001	0.409	140211.95	<0.001	1.0	1936.93	<0.001	0.989
Right Knee	12.25	<0.001	0.368	130336.79	<0.001	1.0	1786.39	<0.001	0.988
Right Mid-thigh	11.84	<0.001	0.361	98099.18	<0.001	1.0	1353.53	<0.001	0.985
Right Upper-thigh	12.22	<0.001	0.368	121148.13	<0.001	1.0	1683.22	<0.001	0.988
Function	9.7	<0.001	0.316	188568.84	<0.001	1.0	2675.2	<0.001	0.992
Appearance	36.58	<0.001	0.635	865741.0	<0.001	1.0	12676.0	<0.001	0.998
Symptoms	9.58	<0.001	0.313	303009.35	<0.001	1.0	4352.07	<0.001	0.995
Mood	44.69	<0.001	0.68	150530.8	<0.001	1.0	2329.6	<0.001	0.991
Overall QOL	98.08	<0.001	0.824	317898.37	<0.001	1.0	4655.74	<0.001	0.996
VAS Pain	22.48	<0.001	0.517	823974.5	<0.001	1.0	7864.25	<0.001	0.997
Stiffness Left Calf	11.66	<0.001	0.357	26586.52	<0.001	0.998	663.57	<0.001	0.969
Stiffness Right Calf	109.21	<0.001	0.839	209224.15	<0.001	1.0	5179.01	<0.001	0.996

Stiffness Left Thigh	11.21	<0.001	0.348	25660.92	<0.001	0.998	648.23	<0.001	0.969
Stiffness Right Thigh	65.49	<0.001	0.757	144570.48	<0.001	1.0	3630.7	<0.001	0.994

Statistical test: Two-way mixed-design ANOVA. Between-subjects factor: Treatment Group (CDT, CDT+TECAR, CDT+ESWT). Within-subjects factor: Time (Baseline, 4 weeks, 8 weeks).

ηp^2 = partial eta squared (effect size): small ≥ 0.01, medium ≥ 0.06, large ≥ 0.14.

G×T = Group × Time interaction. Greenhouse–Geisser correction applied where sphericity assumption was violated ($\varepsilon < 0.75$).

Assumption testing: Normality confirmed for 97.2% of distributions (Shapiro–Wilk $p > 0.05$). Homogeneity of variances verified via Levene's test.

Figures

Figure 1: Limb Circumference (Ankle, Calf) Changes Over Time by Treatment Group. Error bars represent 95% confidence intervals.

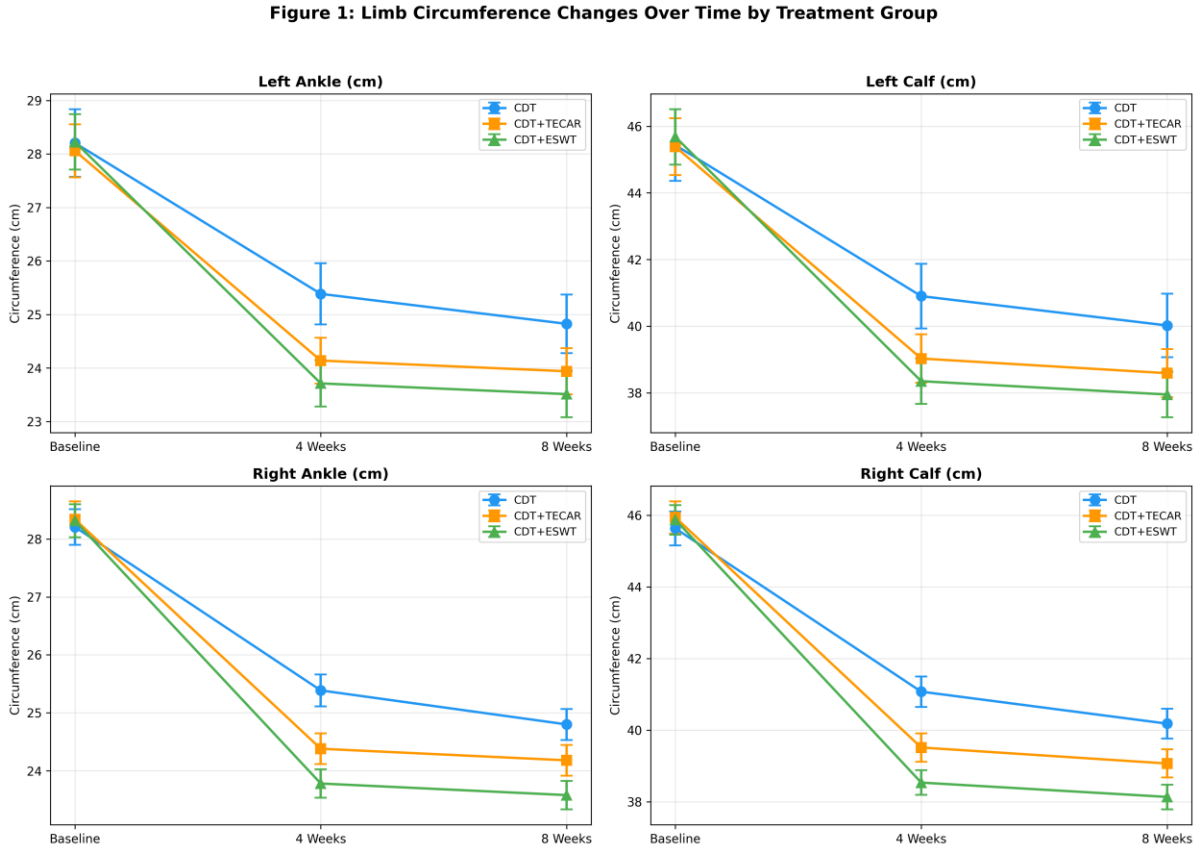

Figure 2: Thigh Circumference Changes Over Time by Treatment Group. Error bars represent 95% confidence intervals.

Figure 2: Thigh Circumference Changes Over Time by Treatment Group

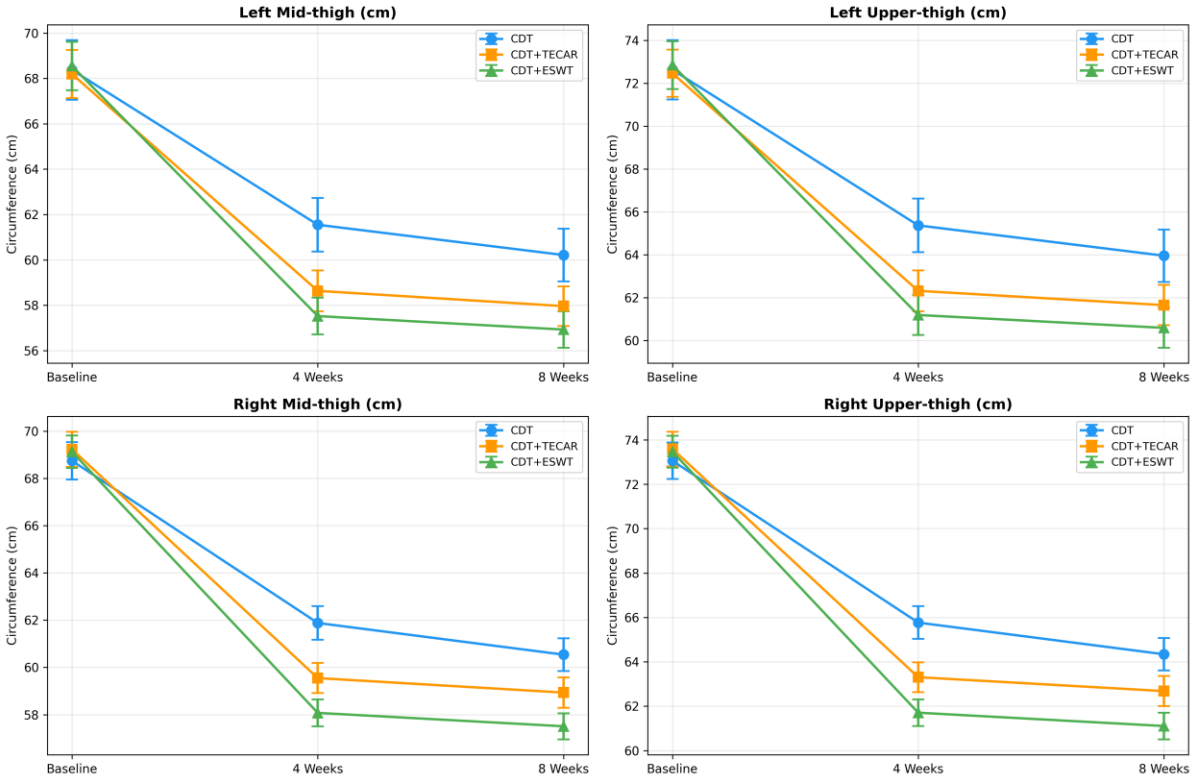

Figure 3: LYMQOL Domain Scores Over Time by Treatment Group. Lower scores indicate better quality of life. Error bars represent 95% confidence intervals.

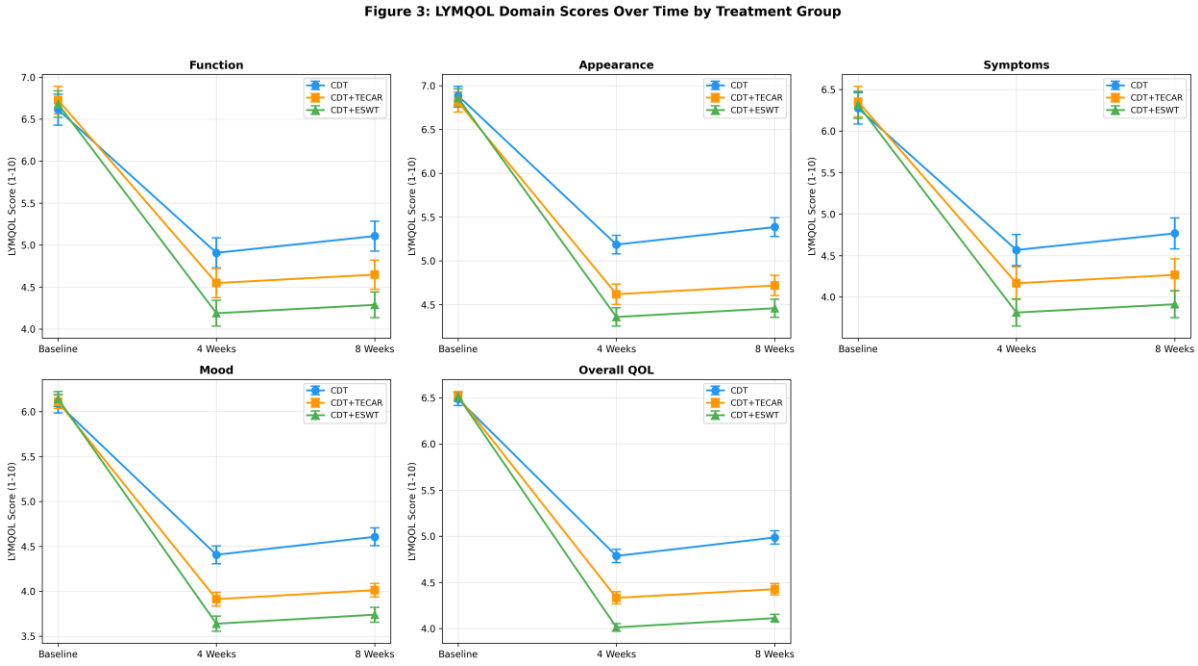

Figure 4: VAS Pain and Tissue Stiffness Over Time by Treatment Group. Error bars represent 95% confidence intervals.

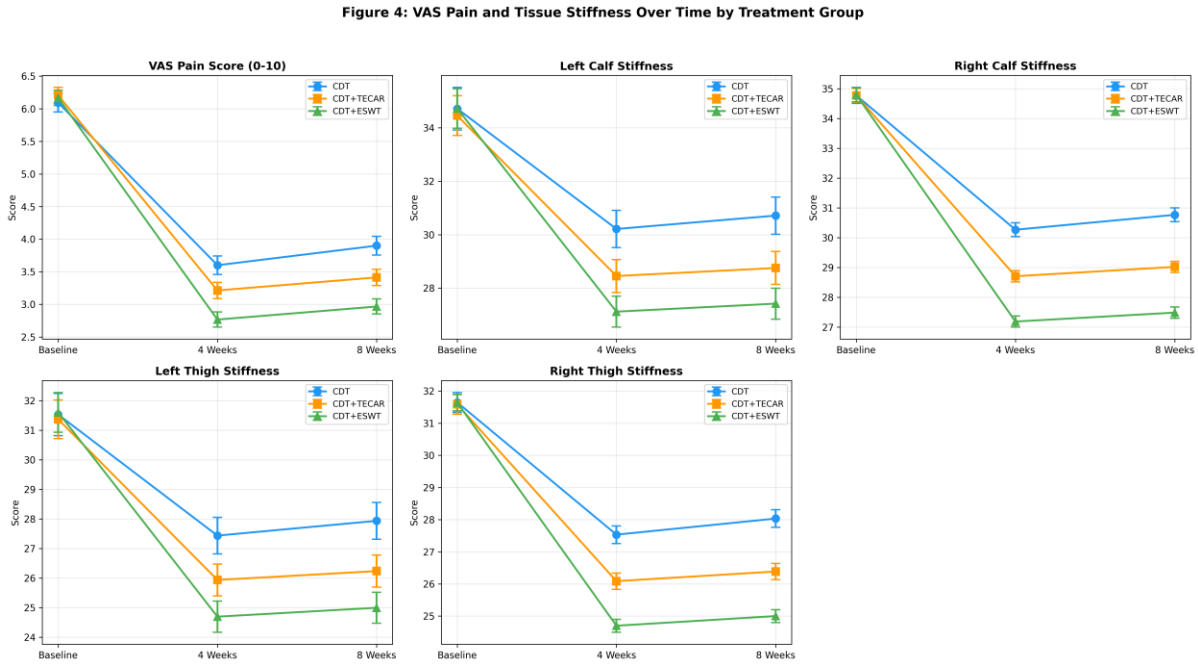

Figure 5: CONSORT Flow Diagram of participant enrollment, allocation, follow-up, and analysis.