AI-Assisted Ultrasound-Guided Galvanic Therapy (AAUGGT) - An Innovative Approach to Pain Management - Fundamental Mechanisms, Biomedical and Technical Development

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DOI: https://doi.org/10.51584/IJRIAS.2025.100700116

Received: 09 July 2025; Accepted: 15 July 2025; Published: 18 August 2025

ABSTRACT

AI-Assisted Ultrasound-Guided Galvanic Therapy (AAUGGT) is an emerging, minimally invasive approach to managing post-inflammatory musculoskeletal pain. This technique combines direct current (galvanic) stimulation with ultrasound imaging for the precise targeting of pathological tissues, further enhanced by artificial intelligence for real-time decision support and treatment optimization. AAUGGT is designed to improve precision, safety, and personalization in conditions such as chronic tendinopathy, myofascial pain, and post-surgical adhesions. The system's architecture combines a handheld probe integrating ultrasound and galvanic electrodes, tissue impedance sensors, and adaptive AI algorithms for image segmentation and dose adjustment. Despite promising early evidence and technical innovation, widespread adoption of AAUGGT faces challenges, including the need for large-scale clinical trials, standardized devices, and regulatory approval. Continued development and multidisciplinary collaboration may establish AAUGGT as a next-generation therapeutic platform in musculoskeletal medicine, with potential for expanded clinical applications and home-based solutions.

Overview: Galvanic therapy, commonly integrated and often interchangeable with Transcutaneous Electrical Nerve Stimulation (TENS), involves the application of low-voltage electrical current to the body. This modality is widely used in physical therapy for musculoskeletal disorders (MSDs), including arthritis, tendonitis, bursitis, phantom limb pain, and soft tissue injuries. Whether applied using direct current (DC) or pulsed biphasic current, the therapeutic goals remain consistent: pain modulation, tissue healing, and functional restoration.

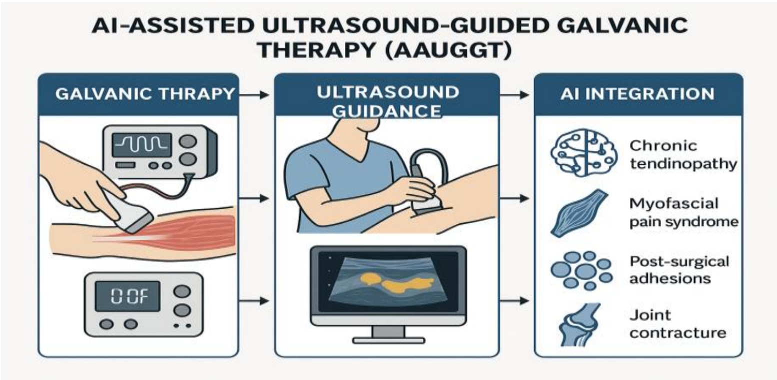

Figure 1. Overview diagram of AAUGGT concept: integration of Galvanic Therapy, Ultrasound Guidance, and AI for musculoskeletal pain management.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VII July 2025

According to Robertson et al. (2006), TENS is one of the most researched electrotherapeutic interventions, with applications ranging from acute trauma management to chronic neuropathic pain syndromes. Similarly, Galvanic stimulation has shown efficacy in soft tissue healing and edema modulation through its polar and vasomotor effects (Michlovitz, 2012).

A novel and transformative development is the integration of AI-assisted ultrasound-guided galvanic therapy, which enables precise targeting of pathological tissues based on real-time imaging and smart feedback algorithms. This approach personalizes stimulation protocols, enhances efficacy, and minimizes patient discomfort or trial-and-error.

INTRODUCTION

Post-inflammatory musculoskeletal pain is a prevalent clinical condition with limited minimally invasive treatments. Galvanic therapy, involving the application of direct current (DC) through tissue, promotes healing, reduces inflammation, and provides pain relief. When combined with ultrasound guidance for precise targeting and artificial intelligence (AI) for real-time decision support, this becomes AI-Assisted Ultrasound-Guided Galvanic Therapy (AAUGGT) a potentially transformative therapeutic modality

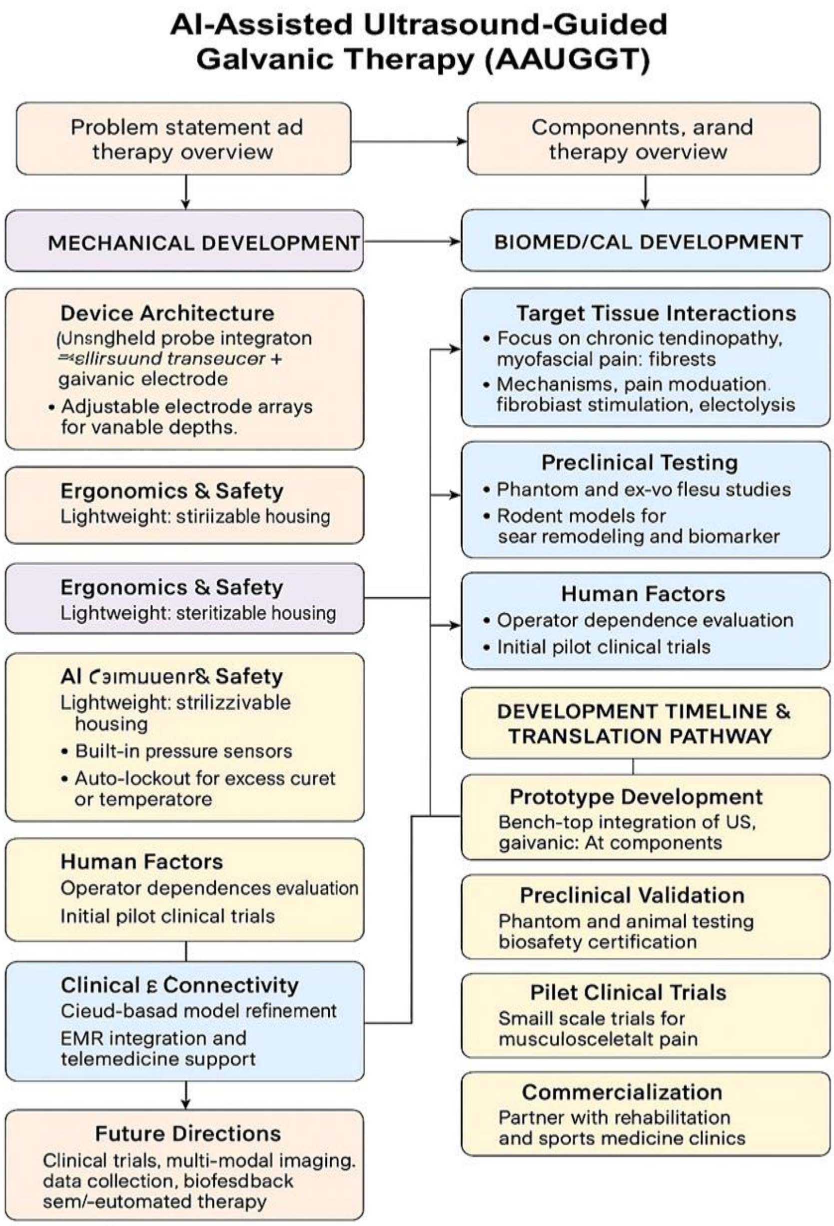

Figure 2. Development Pathway for AI-Assisted Ultrasound-Guided Galvanic Therapy (AAUGGT), outlining mechanical, biomedical, and technical development, as well as the translation timeline

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VII July 2025

Mechanism of Action:

Pain Modulation: Activates A-beta fibers via gate control theory and A-delta/C /C/C fibers for endogenous opioid release.

Polar Effects (when DC is used): - Cathode (-): Alkaline effect, promotes vasodilation and soft tissue relaxation.

Anode (+): Acidic effect, reduces inflammation, and stabilizes scar tissue.

Iontophoresis (Drug Delivery): Transdermal delivery of medications such as dexamethasone to reduce inflammation.

Tissue Repair: Stimulates fibroblast proliferation, angiogenesis, and protein synthesis

Edema Reduction: Enhances lymphatic and venous return through electro-osmosis and muscle pump facilitation.

AI-Assisted Targeting: Advanced image recognition and AI algorithms map inflamed or fibrotic tissues in real time, dynamically adjusting parameters and electrode positioning.

Condition	**Evidence Summary**	**Key Findings**
Knee Osteoarthritis	Moderate	Reduced pain and improved function; more effective when combined with exercise or ultrasound.
Tendinopathies	Moderate	Improved recovery and reduced pain with iontophoresis.
Myofascial Pain Syndrome	Emerging	Reduction in trigger point sensitivity and improved ROM.
Rheumatoid Arthritis	Limited	Minor improvements in stiffness and inflammation.
Post-traumatic Soft Tissue Injury	Strong	Reduces edema and improves circulation and healing.
Phantom Limb Pain	Good	Contralateral TENS reduces pain significantly.

Components of AAUGGT

Galvanic Therapy

Uses direct current to stimulate tissues, improve blood flow, and promote tissue regeneration.

Effective in chronic tendonitis, myofascial trigger points, and post-injury fibrosis.

Ultrasound Guidance

Ensures precise delivery of galvanic current to pathological tissue.

Helps avoid adjacent vessels, nerves, and healthy structures.

Doppler and elastography enhance targeting of inflamed, fibrotic, or ischemic areas.

AI Integration

AI algorithms (e.g., computer vision, deep learning) assist in:

Real-time segmentation of target tissue (e.g., fibrotic bands, trigger points).

Predicting optimal current dosage based on tissue impedance and vascularity.

Adaptive feedback during therapy sessions (e.g., modifying current intensity or duration).

Automating documentation and follow-up tracking via EMR integration.

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Clinical Applications

1. Musculoskeletal Pain Management

AI + ultrasound helps target the exact location of trigger points, fibrotic tissue, or inflamed tendons. Galvanic stimulation is then applied for:

- Tendinopathies (e.g., rotator cuff, patellar tendon)
- Myofascial pain syndrome
- Plantar fasciitis
- Lateral epicondylitis (tennis elbow)

AI's Role:

Identifies hypoechoic (degenerative) regions in tendons and monitors response in real-time (e.g., edema reduction)

2. Nerve Entrapment Syndromes

Ultrasound guided galvanic therapy can be used to stimulate and relieve compression in:

- Carpal tunnel syndrome
- Tarsal tunnel syndrome
- Ulnar nerve entrapment

AI's Role:

- Automatically maps nerve paths from ultrasound frames and assists in distinguishing between nerve and tendon structures

3. Chronic Wound Healing

Galvanic therapy promotes angiogenesis, fibroblast activation, and wound granulation.

Applications:

- Diabetic foot ulcers
- Pressure ulcers
- Venous stasis ulcers

AI's Role:

- Quantifies wound depth, perfusion, and healing progression and predicts healing trajectories using machine learning models

4. Facial Palsy and Neuromodulation

Used in:

- Bell’s palsy
- Post-stroke facial muscle rehabilitation

Galvanic current is applied to facial nerves or motor points under ultrasound, aided by AI for:

- Nerve localization
- Stimulation targeting
- Dose adjustment based on facial symmetry analysis

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5. Trigger Point Therapy and Fibrosis Treatment

In cases of:

- Post-surgical adhesions
- Scar tissue in athletes
- Cervical and lumbar myofascial pain

Contraindications:

- Cardiac pacemakers or defibrillators
- Over malignant lesions or active cancer sites
- Over carotid sinus or anterior neck
- Pregnancy (especially abdominal/lumbar sites)
- Active infections or open wounds
- Cognitive/communication impairments limiting feedback

Advantages of AAUGGT

Precision: Ultrasound ensures targeted therapy, minimizing collateral tissue impact.

Personalization: AI tailors stimulation based on patient-specific anatomy and pathology.

Real-time guidance: AI integrates with ultrasound imaging to provide real-time feedback, reducing user dependence on expert sonographers.

Safety: Reduces risks of misplacement, excessive current, or tissue damage.

Efficiency: AI reduces operator variability and speeds up procedure planning.

Outcome Monitoring: AI can track tissue changes over time, helping in therapy evaluation and patient progress documentation.

Documentation: Automated treatment logs, progress visualization, and patient tracking

Standardization: Reduces operator variability by offering consistent targeting and stimulation protocols across different clinicians.

Challenges and Limitations

Lack of large-scale RCTs: Most evidence is anecdotal or small-scale.

Device standardization: Variation in galvanic and ultrasound device quality.

AI model training: Requires large, annotated datasets for robust accuracy.

User training curve: Practitioners need skill in Ultrasound, electrotherapy, and AI interface.

Regulatory pathway: FDA clearance and safety testing are still hurdles for AI-guided systems.

Device Cost: Advanced AI-assisted ultrasound-guided systems are more expensive than traditional galvanic or ultrasound setups.

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AI-guided systems require training and standardization for clinical integration:

Mode	Frequency	Pulse Duration	Intensity	Electrode Setup	Treatment Time	Effect
High Frequency (Sensory)	50-150 Hz	50-100 µs	Strong tingling	Bipolar/ quadripolar	20 min to 24 hrs	Gate control pain relief
Low Frequency (Motor)	1-10 Hz	200-300 µs	Visible twitch	Over motor points	20-45 min	Endorphin mediated relief
Burst/ Modulated	Varies	Varies	Comfortable to strong	Variable	~20 min	Avoids neural accommo-dation

Future Directions

Clinical Trials: Randomized controlled trials (RCTs) to assess efficacy across conditions.

Data Collection: Multi-center registries with imaging, AI outputs, and patient outcomes.

Multi-modal Imaging: Integration with Doppler, elastography, and MRI for enhanced AI training.

Biofeedback Systems: Using real-time EMG or impedance for closed-loop control.

Wearable AAUGGT: Future potential for semi-automated home-based therapy units.

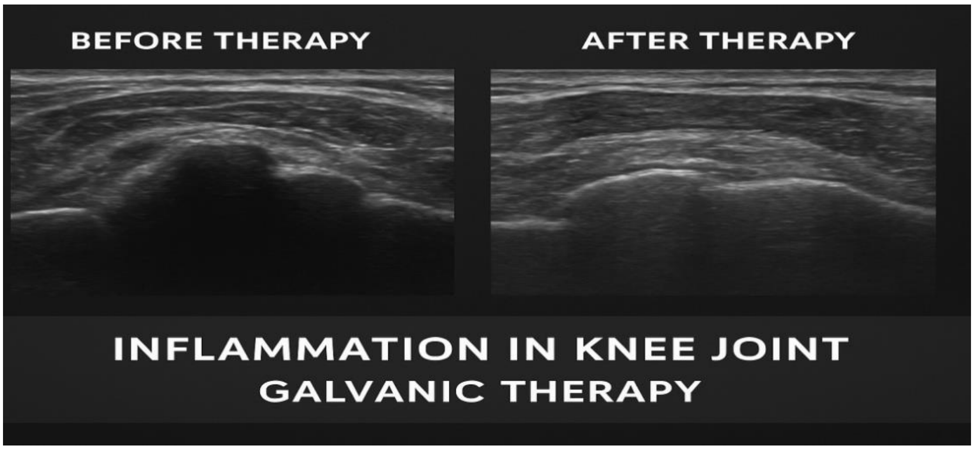

Figure 3. Ultrasound images demonstrate the reduction of inflammation in a knee joint after galvanic therapy

Mechanical Development

a) Device Architecture

Handheld Probe Integration:

Combines an ultrasound transducer and a galvanic electrode in a unified applicator.

Allows real-time imaging and simultaneous DC delivery.

Adjustable Electrode Arrays:

Microelectrode grids are embedded within the applicator.

Adapt to variable tissue depths and geometries (e.g., fascia vs. muscle).

Tissue Impedance Sensors:

Real-time sensors embedded in the probe tip measure electrical resistance, ensuring safe and effective current delivery.

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Modular Design:

Swappable probe heads (linear, curvilinear) for different anatomical regions.

Ergonomics & Safety

Lightweight, sterilizable housing with ergonomic grip.

Built-in pressure sensors to avoid excess probe compression.

Auto-lockout for excessive current or temperature thresholds.

Biomedical Development

Target Tissue Interactions:-

Musculoskeletal Pathologies: Focus on chronic tendinopathy, myofascial pain, fascial fibrosis, scar tissue.

Mechanism of Action: Galvanic current promotes

Cell membrane depolarization → pain modulation.

Fibroblast stimulation → tissue remodeling.

Electrolysis → breakdown of fibrotic tissue.

Synergistic with ultrasound's mechanical effects (e.g., cavitation, thermal softening).

Emerging Trends:

- **AI-Assisted Ultrasound-Guided Galvanic Therapy**: Combines diagnostic ultrasound and artificial intelligence to locate pathological tissue (e.g., tendinosis, fibrosis) and guide precise electrode placement and current modulation in real time.

– **Real-Time Adaptive Algorithms**: Machine learning models continuously refine stimulation settings based on patient feedback, tissue impedance, and observed outcomes.

- Integration with wearable devices for remote rehabilitation

- Smart stimulation protocols with adaptive waveform delivery

This AI-integrated approach is poised to revolutionize the standard of care by eliminating guesswork and standardizing outcomes across diverse patient populations.

Protocol Overview:

1. Electrode Placement:

Apply over the painful area, dermatome, myotome, or acupuncture points. The accurate electrode placement is critical for targeting specific neural pathways, muscles, or pain regions to optimize therapeutic outcomes. When applying at dermatomes, it is important to target sensory nerves along the spinal segments associated with the pain.

When radiculopathy is suspected, myotome testing is a crucial component of the neurological evaluation. Myotome testing is effective for muscle-related conditions and neuromuscular stimulation.

• Protocol for Skin Preparation Guidelines:
• Clean the skin with alcohol or soap and water to remove oils and debris.

• Dry the area completely to reduce skin impedance and prevent hotspots.
• Shave hair if necessary for better electrode adherence.

2. Pad Size and Configuration:

Monopolar for deep tissue targeting. One active electrode is smaller over the treatment area.

Bipolar for general use. Two electrodes of similar sizes are placed over the treatment area.

Common in TENS and general-purpose pain relief

Electrode applications will be done by authorized and trained healthcare professionals.

Larger electrodes: By dispersing current over a larger surface area, larger electrodes minimize pain and lower the current density per square centimeter.

Smaller electrodes can be used for more accurate stimulation; they also increase the current density, which, if used improperly, can be uncomfortable or dangerous.

3. Mode and Frequency Selection:

Selecting the right waveform and frequency ensures the treatment matches the patient's condition and reduces the risk of adaptation.

The goal is to target the pain frequency.

In acute pain - high frequency. For chronic pain - low frequency. Avoid habituation with modulated settings, which will be described below:

The following protocol will be followed:

In TENS (conventional) for sensory-level stimulation without muscle contraction, use high-frequency stimulation (e.g., >50 Hz, commonly 80–120 Hz).

In Chronic Pain, use low-frequency stimulation (e.g., 1–10 Hz).

To Prevent Habituation, use modulated settings, such as:

• Frequency modulation (sweep)
• Intensity modulation
• Burst mode (pulsed high/low alternation)

4. Treatment Frequency:

The treatment frequency will be tailored to each patient, but typically 1–2 sessions per day depending on the severity of the condition and patient response.

The duration of each session will generally be 15–45 minutes per session, adjusted by the protocol and patient comfort.

5. AI Integration/ AI Algorithm:

Use ultrasound imaging to identify pathological structures. The diagnostic ultrasound will be used to locate muscles, tendons, inflammation, or scar tissue. This helps determine depth and direction of the current needed for therapy.

The AI algorithms will help analyze patient-specific data (e.g., imaging, pain score, history) to Recommend optimal electrode placement, waveform, and dosage.

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6. Documentation:

It is an important part of the protocol because it ensures clinical accountability, reproducibility, and legal protection. It will include required information such as, waveform type, frequency, intensity, duration, and electrode placement, and patient response.

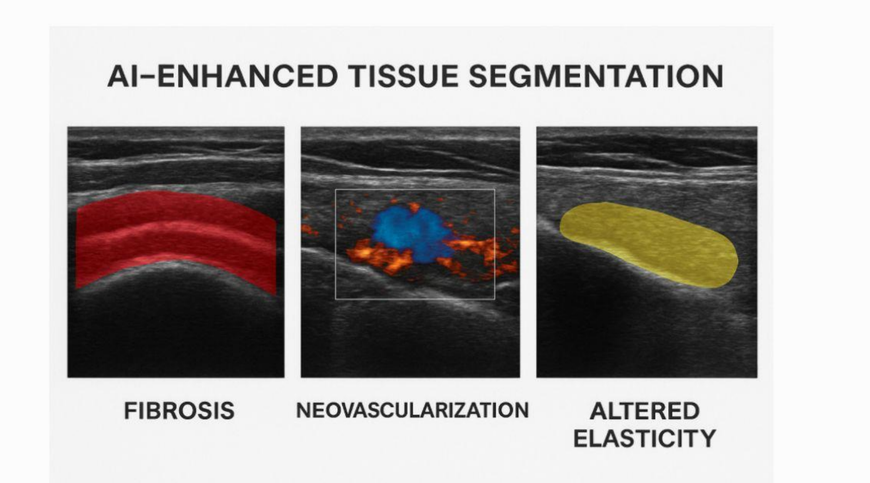

Figure 4. AI-enhanced tissue segmentation showing identification of fibrosis, neovascularization, and altered elasticity in ultrasound images.

Preclinical Testing:

Tissue phantom models for validating current spread and US targeting.

Ex-vivo studies using bovine/porcine tendon and fascia for histologic analysis post-therapy.

Animal studies:

Rodent models for inflammatory pain, scar remodeling.

Evaluation of biomarkers (e.g., collagen I/III ratio, cytokine suppression).

Human Factors:

Evaluation of operator dependence with and without AI assistance.

Initial pilot trials on musculoskeletal pain syndromes under ethical approval.

Technical (AI & Imaging) Development:

Ultrasound Imaging

B-mode, Doppler, and Elastography are integrated into the platform.

AI-enhanced tissue segmentation for:

Identifying fibrosis, neovascularization, or altered elasticity zones.

AI overlays on real-time scans to highlight treatment targets.

AI Components

Computer Vision Algorithms:

Convolutional Neural Networks (CNNs) trained on annotated datasets of target pathologies.

Image registration for probe movement correction.

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Dose Optimization Algorithms:

Adaptive control of current intensity/duration based on:

Tissue impedance.

Pain feedback.

Ultrasound-confirmed tissue response (e.g., stiffness change).

Closed-loop Feedback System:

AI dynamically adjusts current or recommends pause/reposition if response is suboptimal or unsafe.

Data & Connectivity

Cloud-based learning system:

Aggregates anonymized treatment sessions for continuous model refinement.

EMR Integration:

Auto-documentation of therapy parameters, imaging snapshots, and outcome scoring.

Telemedicine Extension:

Remote AI-assisted guidance for clinics with limited MSK expertise.

Development Timeline & Translation Pathway

Phase   Key Milestones

Prototype Development: Bench-top integration of US + galvanic + AI software.

Preclinical Validation: Phantom/animal testing, biosafety certification.

Pilot Clinical Trials: Small-scale trials for pain conditions (e.g., shoulder, low back).

Regulatory Approval: ISO/IEC testing, FDA Class II clearance pathway under 510(k).

Commercialization: Partner with MSK rehab and sports medicine clinics; real-world evidence phase.

Figure 5. various views and components of the TENS & EMS Device, including its packaging, the main unit in its charging case, detached electrode pads, and all accessories.

CONCLUSION

The mechanical fusion of targeted galvanic stimulation and diagnostic ultrasound, enhanced by real-time AI intelligence, positions AAUGGT as a next-gen therapeutic platform. The triad of mechanical precision, biological specificity, and computational adaptability enables high-impact applications in musculoskeletal pain management with scalability to future regenerative therapies.

Galvanic and TENS therapies remain essential components of conservative musculoskeletal management. With the introduction of **AI-assisted ultrasound-guided galvanic therapy**, clinicians can now achieve unprecedented precision in electrode placement and stimulation delivery. Supported by decades of clinical research and cutting-edge technologies, these modalities offer a promising, customizable, and efficient toolset for musculoskeletal pain management. The incorporation of intelligent imaging and real-time algorithmic adjustment offers a truly modernized, patient-specific treatment paradigm. Future large-scale trials are warranted to validate their scalability and long-term benefits in broader patient cohorts

REFERENCES/ BIBLIOGRAPHY:

1. Galvanic Therapy in Musculoskeletal Disorders Abbas, K., et al. (2025). Evaluation of AI-Assisted Ultrasound-Guided Galvanic Therapy (AAUGGT) for the Treatment of Inflammatory-Induced Pain vs other Modalities**.** https://doi.org/10.51584/IJRIAS.2025.10020059
2. Vázquez-Delgado, E., et al. (2012). Electrotherapy for temporomandibular disorders: A systematic review. Journal of Oral Rehabilitation, 39(10), 729–740. https://doi.org/10.1111/j.1365-2842.2012.02322.x
3. Pekyavas, N. O., et al. (2014). Effect of galvanic stimulation on pain and function in musculoskeletal pain syndromes. Clinical Rehabilitation, 28(4), 353–361. https://doi.org/10.1177/0269215513501521
4. Ultrasound Imaging in Musculoskeletal Applications Jacobson, J. A. (2017). Fundamentals of Musculoskeletal Ultrasound (2nd Ed.). Elsevier Health Sciences. ISBN: 978-0323445252
5. Wu, C. H., et al. (2020). Ultrasound elastography for musculoskeletal applications: A systematic review of reliability and validity. Archives of Physical Medicine and Rehabilitation, 101(1), 122–131. https://doi.org/10.1016/j.apmr.2019.07.009
6. AI for Ultrasound and Tissue Segmentation Shen, D., Wu, G., & Suk, H. I. (2017). Deep learning in medical image analysis. Annual Review of Biomedical Engineering, 19, 221–248. https://doi.org/10.1146/annurev-bioeng-071516-044442
7. Zeng, D., et al. (2021). Automated segmentation of musculoskeletal ultrasound using deep learning: A review. Ultrasound in Medicine & Biology, 47(5), 1198–1210. https://doi.org/10.1016/j.ultrasmedbio.2021.01.004
8. Xie, Y., et al. (2020). Semiautomatic segmentation of Achilles tendon ultrasound images using deep neural networks. Medical Physics, 47(9), 4246–4254. https://doi.org/10.1002/mp.14358
9. Doppler Ultrasound & Neovascularization Rees, J. D., et al. (2008). Neovascularization in tendinopathy: From imaging to therapeutic targeting. Nature Clinical Practice Rheumatology, 4(6), 301–309. https://doi.org/10.1038/ncprheum0783
10. Cook, J. L., et al. (2018). Doppler ultrasound and color flow mapping in chronic tendinopathies: A clinical review. British Journal of Sports Medicine, 52(19), 1220–1224. https://doi.org/10.1136/bjsports-2017-098698
11. AI Model Architecture (Segmentation) Ronneberger, O., et al. (2015). U-Net: Convolutional networks for biomedical image segmentation. Medical Image Computing and Computer-Assisted Intervention (MICCAI). https://doi.org/10.1007/978-3-319-24574-4_28
12. Çiçek, Ö., et al. (2016). 3D U-Net: Learning dense volumetric segmentation from sparse annotation. MICCAI. https://doi.org/10.1007/978-3-319-46723-8_49
13. Medical Software Development Standards IEC 62304:2006/Amd 1:2015. Medical device software – Software life cycle processes. International Electrotechnical Commission.
14. U.S. FDA. (2022). Artificial Intelligence and Machine Learning (AI/ML)-Based Software as a Medical Device (SaMD). https://www.fda.gov/media/145022/download
15. Clinical Integration and Safety of AI-Guided Tools Topol, E. J. (2019). High-performance medicine: the convergence of human and artificial intelligence. Nature Medicine, 25(1), 44–56. https://doi.org/10.1038/s41591-018-0300-7
16. Liu, X., et al. (2019). A comparison of deep learning performance against health-care professionals in detecting diseases from medical imaging: A systematic review and meta-analysis. The Lancet Digital Health, 1(6), e271–e297. https://doi.org/10.1016/S2589-7500(19)30123-2

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VII July 2025

17. Galvanic Therapy Device Integration with Imaging Rutkove, S. B. (2009). Electrical impedance myography: Background, current state, and future directions. Muscle & Nerve, 40(6), 936–946. https://doi.org/10.1002/mus.21411
18. Radecki, D. R., et al. (2018). Ultrasound-guided electrostimulation: A new frontier in neuromodulation. Pain Medicine, 19(Suppl_1), S30–S38. https://doi.org/10.1093/pm/pnx195