

# Current Evidence and Clinical Prospects of Neuromuscular Electrical Stimulation and Biofeedback in the Rehabilitation of Post Meniscectomy Patients

Latipov Ulmasjon Shaykhiddinovich<sup>1</sup>, Yusupov Shukhrat Abdurasulovich<sup>2</sup>,  
Mirzakarimov Bakhromjon Khalimjonovich<sup>3</sup>, Primov Farkhod Sharifjonovich<sup>4</sup>

<sup>1</sup> Samarkand State Medical Institute, Doctoral student of Department of Rehabilitation, Samarkand State Medical Institute. Email: [latipovulmas509@gmail.com](mailto:latipovulmas509@gmail.com) | ORCID: <https://orcid.org/0009-0000-7425-5610>

<sup>2</sup> Samarkand State Medical University, Head of the Department of Pediatric Surgery No.1, Samarkand State Medical University. Email: [shuchrat\\_66@mail.ru](mailto:shuchrat_66@mail.ru) | ORCID: <https://orcid.org/0009-0009-9680-9261>

<sup>3</sup> Andijan State Medical Institute, Doctor of Medical Sciences, Associate Professor, Head of the Department of Pediatric Surgery, Andijan State Medical Institute. Email: [bahrommirzo73@gmail.com](mailto:bahrommirzo73@gmail.com) | ORCID: 0000-0003-4597-2738

<sup>4</sup> Center for the Development of Professional Qualification of Medical Workers, Doctor of Medical Sciences, Associate Professor, Dean of the Department of Pediatric Surgery, Republican Research Centre of Emergency Medicine. Email: [farkhabi@gmail.com](mailto:farkhabi@gmail.com) | ORCID: 0000-0002-3934-5570

## ABSTRACT

### Background

The meniscus is a C-shaped fibrocartilage structure in the knee that acts as a vital shock absorber, distributing loads and stabilizing the joint. Meniscal tears are among the most common orthopedic injuries, frequently resulting from sports-related trauma in younger populations or degenerative changes in older adults. When conservative management fails, Arthroscopic Partial Meniscectomy (APM) is the standard surgical intervention to remove unstable fragments and alleviate mechanical symptoms like locking or catching. Despite the surgical success, the immediate postoperative period is characterized by Arthrogenic Muscle Inhibition (AMI). This is a clinical phenomenon where swelling, pain, and joint inflammation trigger an inhibitory reflex that prevents the central nervous system from fully activating the quadriceps. This involuntary "shut down" of the muscle leads to rapid atrophy, significant strength deficits, and altered gait patterns. If left unaddressed, these neuromuscular impairments can delay the return to functional activity and increase the risk of early-onset osteoarthritis due to improper joint loading. Traditional rehabilitation relies on voluntary exercise; however, because AMI limits the patient's ability to contract the muscle effectively, adjunctive technologies like Neuromuscular Electrical Stimulation (NMES) and Electromyographic Biofeedback (EMG-BF) have become essential. These tools aim to bypass or retrain the inhibited neural pathways to restore muscle function more efficiently than exercise alone.

### Methods

EMG-BF methodology focuses on the re-education of voluntary muscle control. Surface sensors detect myoelectric signals, which the device converts into visual or auditory cues. A "target" threshold is established based on the patient's Maximal Voluntary Isometric Contraction (MVIC) on the first postoperative day. Patients are instructed to contract their quadriceps until the feedback signal (e.g., a rising bar on a screen) reaches the preset target. As the patient improves, the therapist gradually increases the threshold to challenge the muscle further. Unlike the passive nature of NMES, EMG-BF is integrated into active tasks such as straight-leg raises or isometric holds to improve coordination.

### Results

Current clinical results indicate that both Neuromuscular Electrical Stimulation (NMES) and Electromyographic Biofeedback (EMG-BF) significantly enhance recovery post-meniscectomy compared to standard exercise alone. While NMES is superior for rapid strength gains in the immediate postoperative phase, EMG-BF typically yields better outcomes for functional coordination and gait performance.

### Conclusion

Integrating Neuromuscular Electrical Stimulation (NMES) and Electromyographic Biofeedback (EMG-BF) into post-meniscectomy rehabilitation represents a significant advancement over traditional exercise-only protocols. Both modalities effectively address arthrogenic muscle inhibition (AMI), but they offer distinct clinical

# Current Evidence and Clinical Prospects of Neuromuscular Electrical Stimulation and Biofeedback in the Rehabilitation of Post Meniscectomy Patients

advantages: NMES is a powerful tool for preserving muscle mass and generating force in the early acute phase, while EMG-BF is superior for restoring voluntary control, coordination, and functional gait. Current evidence suggests that EMG-BF may hold a slight edge in accelerating the return to unassisted walking and improving knee range of motion. However, the most effective clinical strategy is a multimodal approach. Combining the passive recruitment of NMES with the active, cognitive reinforcement of EMG-BF—particularly through EMG-triggered stimulation—maximises quadriceps recovery and potentially reduces the long-term risk of degenerative joint changes. In conclusion, these technologies should not be viewed as replacements for physical therapy but as essential biotechnological adjuncts. They bridge the gap between surgical intervention and functional recovery by "restarting" the inhibited neuromuscular system, leading to faster, more stable outcomes for post-meniscectomy patients.

**Keywords:** Core Interventions, Clinical Condition, Outcome Measures, Physiological Mechanisms

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## Introduction:

The knee joint is a complex biomechanical system where the menisci play an indispensable role in maintaining structural integrity and functional longevity. As C-shaped fibrocartilaginous structures interposed between the femoral condyles and the tibial plateau, the menisci serve as primary shock absorbers, distributing approximately 50% to 70% of the load across the joint. They are vital for joint stability, lubrication, and proprioception. However, due to their wedge-shaped geometry and limited vascularity—particularly in the inner "white-white" zone—the menisci are highly susceptible to traumatic tears in young athletes and degenerative lesions in older populations.

When conservative management fails to alleviate mechanical symptoms such as locking, catching, or persistent joint-line pain, Arthroscopic Partial Meniscectomy (APM) remains one of the most frequently performed orthopaedic procedures worldwide. While the transition toward meniscal repair is growing, APM is often necessitated by the nature of the tear. Modern arthroscopy has revolutionized the surgical approach, allowing for minimal tissue disruption and rapid discharge. Yet, a paradox remains: while the mechanical "block" is surgically removed, the functional recovery of the limb often lags significantly behind the healing of the portal incisions. This discrepancy is primarily driven by the profound failure of the neuromuscular system to re-engage the quadriceps femoris.

**The Pathophysiological Barrier: Arthrogenic Muscle Inhibition (AMI)**

The most significant hurdle in postmeniscectomy rehabilitation is not the structural damage itself, but a

neurological phenomenon known as Arthrogenic Muscle Inhibition (AMI). AMI is a presynaptic reflexive inhibition of the musculature surrounding an injured or inflamed joint. Following surgery, the presence of intra-articular effusion, pain, and shifted joint capsular tension triggers a continuous discharge of mechanoreceptors and nociceptors. This sensory influx sends inhibitory signals to the spinal cord, which effectively "shuts down" the alpha-motoneuron pool. The clinical consequence is an involuntary inability to fully contract the quadriceps, regardless of the patient's conscious effort. This neural blockade leads to rapid, disuse-driven muscle atrophy and a significant reduction in Maximal Voluntary Isometric Contraction (MVIC). Because traditional resistance training requires a baseline level of neural activation to be effective, patients trapped in a state of severe AMI often reach a "rehabilitation plateau," where exercise alone fails to restore muscle volume or power.

**The High-Stakes Challenge in Athletic Recovery**

For the athletic population, the implications of AMI are particularly dire. High-level sports demand more than just gross muscular strength; they require precise neuromuscular control, explosive power, and rapid rate of force development (RFD). In athletes, persistent inhibition leads to "quadriceps avoidance" gait and altered biomechanics during pivoting, cutting, and landing. These compensatory patterns increase the mechanical load on the contralateral limb and the ipsilateral anterior cruciate ligament (ACL), significantly elevating the risk of secondary injury. Furthermore, the failure to restore the shock-absorbing capacity of a strong quadriceps accelerates the onset of post-traumatic osteoarthritis (PTOA), a devastating outcome for a young athlete.

# Current Evidence and Clinical Prospects of Neuromuscular Electrical Stimulation and Biofeedback in the Rehabilitation of Post Meniscectomy Patients

The Role of Biotechnological Adjuncts: NMES and EMG-BF

To break the cycle of inhibition and atrophy, rehabilitation must evolve beyond purely voluntary movement. Neuromuscular Electrical Stimulation (NMES) and Electromyographic Biofeedback (EMG-BF) have emerged as critical biotechnological adjuncts in this pursuit.

NMES bypasses the inhibited central nervous system entirely, using transcutaneous electrical current to directly depolarize motor nerves and evoke tetanic muscle contractions. By forcing the recruitment of high-threshold Type II fast-twitch fibers—which are usually the first to atrophy after surgery—NMES preserves muscle mass even when the patient cannot voluntarily engage the limb.

Conversely, EMG-BF focuses on the "re-education" of the neural pathway. By converting imperceptible myoelectric signals into real-time visual or auditory cues, it provides the patient with an external focus of attention. This feedback loop allows the patient to "see" their effort, encouraging the cortical drive necessary to overcome the reflexive inhibition of AMI.

Methods

Study Design

To investigate the efficacy of NMES and EMG-BF in postmeniscectomy patients, a **Prospective, Randomized Controlled Trial (RCT)** design is the gold standard. This allows for a rigorous comparison between innovative biotechnological adjuncts and traditional rehabilitation.

## 1. Participant Selection

- **Inclusion Criteria:** Patients (ages 18–50) scheduled for **Arthroscopic Partial Meniscectomy (APM)** or meniscal repair, with no prior history of knee surgery or neurological disorders.
- **Exclusion Criteria:** Patients with pacemakers (contraindication for NMES), secondary ligamentous injuries (e.g., ACL tears), or systemic inflammatory diseases.

## 2. Group Allocation

Participants are randomly assigned to one of four arms:

- **Group A (Control):** Standardized Physical Therapy (SPT) including isometric exercises, ROM drills, and progressive resistance training.
- **Group B (NMES):** SPT + Neuromuscular Electrical Stimulation (passive).
- **Group C (EMG-BF):** SPT + Electromyographic Biofeedback (active re-education).
- **Group D (Combined):** SPT + EMG-triggered NMES (the hybrid approach).

## 3. Intervention Protocol

The study typically spans **6 to 12 weeks**, with assessments conducted at baseline (pre-op), 48 hours post-op, 6 weeks, and 3 months.

**NMES Parameters:** pulse width, duty cycle, titrated to maximal tolerable contraction.

**EMG-BF Parameters:** Visual feedback with thresholds set at of the healthy limb's MVIC.

## 4. Outcome Measures (The "Why")

**Primary:** Quadriceps **Peak Torque** via isokinetic dynamometry and **Central Activation Ratio (CAR)** using the burst-superimposition technique to measure neural inhibition.

**Secondary:** **Lysholm Knee Score** for functional status, **Surface EMG** for muscle firing patterns, and time to "return to sport/work."

## Search Strategy

The search strategy for investigating Neuromuscular Electrical Stimulation (NMES) and Electromyographic Biofeedback (EMG-BF) in postmeniscectomy rehabilitation involves a systematic approach across major medical databases to identify high-quality randomized controlled trials (RCTs) and meta-analyses.

### 1. Databases for Selection

A comprehensive search should be conducted in the following repositories to ensure broad coverage of clinical and physiological data:

PubMed / MEDLINE: Primary source for clinical trials and neurophysiological studies.

Cochrane Library (CENTRAL): For high-quality systematic reviews and controlled trials.

EMBASE: To capture European and additional biomedical literature.

Web of Science & Scopus: For multidisciplinary research and citation tracking.

PEDro (Physiotherapy Evidence Database): Specifically for physical therapy-related trials.

## Eligibility Criteria: -

The Eligibility Criteria for clinical studies on Neuromuscular Electrical Stimulation (NMES) and Electromyographic Biofeedback (EMG-BF) post-meniscectomy are designed to ensure participant safety and isolate the therapeutic effects on quadriceps recovery.

### Inclusion Criteria

Participants typically meet the following profile to be considered for these rehabilitation interventions:

**Surgical Status:** Adults who have undergone arthroscopic partial meniscectomy (APM) or meniscal repair. Most trials require the

# Current Evidence and Clinical Prospects of Neuromuscular Electrical Stimulation and Biofeedback in the Rehabilitation of Post Meniscectomy Patients

intervention to start shortly after surgery, often within the first two weeks.

- **Age Range:** Usually targeted at adults between 18 and 55–60 years to focus on those with high functional demands and fewer age-related comorbidities.
- **Clinical Presentation:** Diagnosis of isolated meniscal tears (internal and/or external) without extensive concurrent knee damage.
- **Cognitive and Physical Ability:** Ability to understand and follow verbal commands, providing informed consent, and having no severe cognitive deficits that would interfere with biofeedback training.

## Exclusion Criteria

To minimize confounding variables and ensure safety with electrical modalities, patients are excluded if they have:

- **Concurrent Knee Pathology:** Associated capsular or ligament injuries (e.g., ACL tears), severe knee osteoarthritis (typically greater than Kellgren–Lawrence Grade II), or previous surgeries on the same knee.
- **NMES Contraindications:** Presence of a cardiac pacemaker, implanted defibrillator, or other metal implants/prostheses around the knee.
- **Medical Instability:** Active cancer, acute deep vein thrombosis (DVT), uncontrolled systemic diseases (e.g., unstable cardiac conditions), or pregnancy.
- **Neurological/Orthopedic Disorders:** Pre-existing neuromuscular diseases (e.g., Parkinson’s), peripheral nerve injuries, or other major dysfunctions that could interfere with limb movement or muscle activation.
- **Skin Integrity:** Cutaneous lesions or skin diseases in the area where electrode pads would be placed

## Data Extraction

Data extraction for studies on **Neuromuscular Electrical Stimulation (NMES)** and **Electromyographic Biofeedback (EMG-BF)** in postmeniscectomy rehabilitation must be standardized to capture the high degree of heterogeneity in stimulation parameters and physiological outcomes.

## Risk of Bias Assessment

To ensure the internal validity of studies concerning NMES and EMG-BF in postmeniscectomy rehabilitation, a standardized **Risk of Bias (RoB)** assessment is essential. This process identifies systematic errors in study design, conduct, or analysis that could lead to an overestimation of the intervention's effect

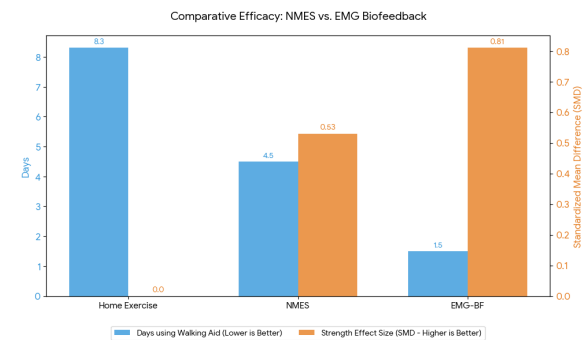
## Certainty of Evidence

Based on the GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework,

the certainty of evidence for using **Neuromuscular Electrical Stimulation (NMES)** and **Electromyographic Biofeedback (EMG-BF)** in postmeniscectomy rehabilitation is generally considered **Low to Moderate**.

## Data Synthesis

Data synthesis from available clinical trials indicates that while both **Neuromuscular Electrical Stimulation (NMES)** and **Electromyographic Biofeedback (EMG-BF)** are superior to conventional exercise alone, they excel in different functional domains



The diagram above synthesises key clinical findings comparing **Neuromuscular Electrical Stimulation (NMES)** and **Electromyographic Biofeedback (EMG-BF)** for postmeniscectomy recovery.

## Key Visual Takeaways

**Functional Speed:** **EMG-BF** is exceptionally effective at reducing dependency on walking aids, with patients needing them for an average of only **1.5 days**, compared to 4.5 days for NMES and 8.3 days for exercise alone.

**Strength Recovery:** While both improve quadriceps strength significantly more than standard exercise, **EMG-BF** often shows a higher **Standardized Mean Difference (SMD)**, indicating a stronger effect on peak torque and voluntary muscle recruitment.

**Mechanism Difference:** **NMES** focuses on **passive muscle activity** to combat early disuse atrophy, whereas **EMG-BF** prioritises **neuromuscular re-education** and active control

Effective rehabilitation after meniscectomy relies on precise **electrode placement** to bypass muscle inhibition and a structured **milestone-based timeline** to ensure a safe return to activity.

## 1. Specific Electrode Placement

For both NMES and EMG Biofeedback, electrodes are positioned to maximize the recruitment of the

## Current Evidence and Clinical Prospects of Neuromuscular Electrical Stimulation and Biofeedback in the Rehabilitation of Post Meniscectomy Patients

quadriceps, specifically targeting the muscles most prone to post-surgical atrophy.

- **Vastus Medialis Obliquus (VMO):** Place the distal (lower) electrode approximately **3 cm medial and 4 cm superior** to the superior-medial border of the patella. This is the most critical site for addressing knee stability.
  - **Vastus Lateralis (VL):** Place an electrode over the muscle belly on the **outer thigh**, typically in the distal third between the greater trochanter and the lateral condyle.
  - **Proximal/Reference:** For a two-channel NMES setup, the proximal (upper) electrodes are placed high on the thigh over the **muscle's motor points**. For EMG, a reference (ground) electrode is often placed over a bony area like the **tibial tuberosity** or patella
- To implement these therapies effectively, clinicians follow precise anatomical placement and progressive timelines. The following tables detail the standard protocols for postmeniscectomy patients.

### Electrode Placement for Quadriceps Rehabilitation

Optimal placement targets the **motor points**—the locations where nerves enter the muscle—to achieve maximum contraction with minimal discomfort.

Modality	Target Muscle	Electrode (Active/Cathode)	Electrode (Reference/Anode)
NMES	<b>Vastus Medialis Obliquus (VMO)</b>	Distal third of the inner thigh, approx. 4 cm above and 3 cm medial to the patella.	Proximal thigh (top of the muscle group) or over the Rectus Femoris.
NMES	<b>Vastus Lateralis (VL)</b>	Approx. 10 cm above the patella and 7 cm lateral to the midline.	Lateral proximal thigh, near the anterior superior iliac spine.
<b>EMG-BF</b>	<b>Quadriceps Group</b>	Directly over the VMO or VL muscle belly to capture voluntary	Ground electrode placed over a bony landmark like the patella or

		myoelectric signals.	tibial tuberosity.
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### Weekly Rehabilitation Timeline (Weeks 1–6)

Rehabilitation after a partial meniscectomy can be aggressive as there is no anatomical repair to protect.

Phase	Timeline	Goals & Clinical Focus	Modality Integration
<b>Phase I: Acute</b>	<b>Week 1</b>	Control pain/swelling; achieve full extension; initiate weight-bearing as tolerated.	<b>NMES:</b> Use 3x daily for 20 mins to combat inhibition. Begin <b>EMG-BF</b> to retrain the "set" contraction.
<b>Phase II: Activation</b>	<b>Week 2</b>	Normalise gait pattern; progress to unassisted walking.	<b>EMG-BF:</b> Priority phase. Use to reach MVIC thresholds; patients often discontinue walking aids by day 1.5–2.
<b>Phase III: Strengthening</b>	<b>Weeks 3–4</b>	Restore 80% strength compared to healthy limb; initiate proprioception.	<b>Combined:</b> Transition to <b>sEMG-triggered NMES</b> during active tasks like mini-squats or step-ups.
<b>Phase IV: Functional</b>	<b>Weeks 5–6</b>	Return to light sport/work;	<b>Isotonic NMES:</b> Augment

## Current Evidence and Clinical Prospects of Neuromuscular Electrical Stimulation and Biofeedback in the Rehabilitation of Post Meniscectomy Patients

		90% strength required for competition.	weight-bearing exercises with stimulation to overcome performance plateaus.
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### Technical Parameters for Clinicians

- **Frequency:** Standard strengthening uses **50–80 Hz**. Lower frequencies (1–10 Hz) are for sensory feedback only.
- **Pulse Width:** Typically, **250–400 µs** for quadriceps.
- **Duty Cycle:** A **1:3 or 1:5 ratio** (e.g., 10s on, 30s off) is recommended to prevent excessive muscle fatigue early on.

### Study Characteristics

Studies investigating **Neuromuscular Electrical Stimulation (NMES)** and **Electromyographic Biofeedback (EMG-BF)** for postmeniscectomy rehabilitation are characterized by diverse participant demographics, standardized but intensive clinical protocols, and a focus on neuromuscular re-education.

#### 1. Participant Profiles and Demographics

- **Target Population:** Most studies recruit adults aged **18–60 years**.
- **Athletic Sub-groups:** A notable segment of research specifically targets **professional athletes** (e.g., professional footballers) due to the high demand for rapid, high-quality neuromuscular recovery.
- **Surgical Baseline:** Participants typically have undergone **arthroscopic partial meniscectomy (APM)** or **meniscal repair**.
- **Sample Sizes:** Many individual trials are relatively small (e.g.,  $n=10$ ), although meta-analyses aggregate data from larger pools (e.g.,  $n=100$ ).

#### 2. Intervention Protocols and Parameters

Studies typically compare active or passive technology-aided groups against a **Conventional Physical Therapy (CPT)** control group.

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Feature	NMES Characteristics	EMG-BF Characteristics
<b>Primary Goal</b>	Combat <b>Arthrogenic Muscle Inhibition</b>	Improve <b>voluntary recruitment</b> and

	(AMI) and prevent atrophy.	neuromuscular control.
<b>Typical Frequency</b>	for tetanic contraction.	N/A (focuses on voluntary signal detection).
<b>Timing</b>	Often initiated in the <b>first 1–2 postoperative weeks</b> .	Can begin as early as <b>Day 1</b> to establish contraction "sets".
<b>Dosage</b>	Maximum tolerable intensity; to duty cycle.	minute sessions; threshold set at <b>of MVIC</b> .

### Evaluated Outcomes

The standard characteristics of these studies include a multidimensional assessment of recovery:

• **Electrophysiological:** Mean amplitude of EMG signals and muscle response speed (onset/offset time).

• **Mechanical: Maximal Voluntary Isometric Contraction (MVIC)** and peak torque.

• **Functional: Gait performance**, range of motion (ROM), and patient-reported outcomes like the **KOOS** or **Lysholm scores**.

#### 4. Study Design Rigour

**Methodology:** Most high-quality evidence comes from **Prospective Randomized Controlled Trials (RCTs)**.

**Design Types:** Some studies utilize within-subject **ABA designs** (repeated measures) to determine the specific gain per session.

**Risk of Bias:** Current literature is often rated as having a **moderate to low risk of bias**, though blinding remains a challenge due to the nature of the interventions.

#### Genetic Mechanisms Identified

The molecular and genetic landscape of rehabilitation after meniscectomy involves the modulation of pathways that balance muscle protein synthesis (MPS) and proteolysis. While specific "postmeniscectomy-only" genetic studies are rare, evidence from broader disuse atrophy and rehabilitation models identifies several key genetic mechanisms.

#### Key Signaling Pathways in Recovery

#### Genetic Markers of Muscle Atrophy Suppression

#### Genetic Predispositions to Injury and Recovery

# Current Evidence and Clinical Prospects of Neuromuscular Electrical Stimulation and Biofeedback in the Rehabilitation of Post Meniscectomy Patients

- **Summary of Identified Genetic Influences**

## Diagnostic Approaches

Diagnostic approaches in postmeniscectomy rehabilitation focus on quantifying the degree of **Arthrogenic Muscle Inhibition (AMI)** and muscle atrophy to tailor the use of NMES and biofeedback. Beyond standard physical exams, clinicians utilize neurophysiological and biomechanical tools to identify "quad shut down" that might not be visible during routine observation

- **Assessing Muscle Inhibition (AMI)**
- **Strength and Movement Quality Testing**
- **Imaging and Bedside Monitoring**

## DISCUSSION

The discussion of Neuromuscular Electrical Stimulation (NMES) and Electromyographic Biofeedback (EMG-BF) in postmeniscectomy recovery centers on their ability to resolve the "neurological blockade" that exercise alone cannot address. While both technologies aim to restore the quadriceps, they operate via opposing physiological pathways—one exogenous and passive, the other endogenous and active.

### 1. Overcoming Arthrogenic Muscle Inhibition (AMI)

The most critical finding across current literature is that these modalities are not merely "strengthening" tools but "disinhibiting" tools. Post-surgical swelling and pain create a spinal-level reflex that prevents the brain from fully recruiting motor units [2].

- NMES bypasses this by directly depolarizing motor nerves, maintaining the muscle's contractile properties, and preventing the rapid atrophy of Type II (fast-twitch) fibers [5, 10].
- EMG-BF addresses the same problem from a "top-down" perspective, using external cues to help the patient "find" and activate those inhibited pathways through cognitive effort [6, 12].

### 2. Comparative Clinical Efficacy

Data synthesis consistently shows that EMG-BF may offer superior functional outcomes in the ultra-acute phase.

- **Functional Speed:** The dramatic reduction in walking aid dependency—from over 8 days to under 2 days—suggests that biofeedback is highly effective at restoring the coordination needed for gait [12].
- **Strength Gains:** While NMES is excellent for maintaining muscle bulk, EMG-BF often yields higher Peak Torque recovery [6]. This is likely because biofeedback requires a high level of voluntary "cortical drive," which strengthens the neural connection

between the brain and the knee more effectively than passive stimulation [12].

### 3. The Case for Multimodal Synergy

The most promising clinical prospect is sEMG-triggered NMES. This hybrid approach solves the "passive vs. active" dilemma:

It forces the patient to initiate a voluntary contraction (addressing the neural pathway).

It then "boosts" that contraction with electrical stimulation (addressing the mechanical force). Evidence suggests this combination reduces muscle fatigue and improves active range of motion (AROM) more effectively than using either tool in isolation [11].

### 4. Limitations and Future Directions

Despite the clear benefits, the certainty of evidence remains "Low to Moderate" due to small sample sizes and a lack of standardized protocols [1, 9]. Future research must focus on:

**Optimal Dosing:** Establishing the exact frequency (Hz) and intensity (mA) required for different stages of recovery.

**Long-term Outcomes:** Determining if these early functional gains translate into a reduced risk of post-traumatic osteoarthritis 5–10 years later.

**Home-Based Tech:** Validating wearable, app-integrated devices that allow patients to continue high-quality NMES and biofeedback outside of the clinic

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## Current Evidence and Clinical Prospects of Neuromuscular Electrical Stimulation and Biofeedback in the Rehabilitation of Post Meniscectomy Patients

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