

Integrative Application of Neuromuscular Electrical Stimulation in Musculoskeletal Disorders

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Abstract:

Neuromuscular electrical stimulation (NMES) is a non-invasive technique that activates motor nerves to induce muscle contractions, thereby preserving muscle strength in patients who are unable to perform high-intensity voluntary exercise. While increasingly integrated into musculoskeletal rehabilitation, the additional benefits, optimal parameters, and indications of this approach remain debated. This systematic review synthesizes evidence on NMES as an adjunctive therapy for knee osteoarthritis (KOA), patellofemoral pain (PFP), chronic low back pain (CLBP), total knee arthroplasty (TKA), anterior cruciate ligament (ACL) reconstruction, shoulder surgery, ICU-acquired weakness (ICUAW), and sarcopenia. The results indicate that NMES in conjunction with exercise therapy has synergistic effects in the areas of pain relief, muscle strength improvement and functional recovery. The therapeutic action is time-dependent. Initiation early (within 48 hours to 1 week post-surgery) proves beneficial. Chronic pain conditions need more than 4 weeks of treatment to achieve meaningful improvement. Parameters suggested are in KOA 50-75Hz, pulse length 200-400 μ s, and at least 20 minutes per session. After knee surgery, initiate in the first 2 weeks, frequency $\geq$ 50Hz, and maximum tolerable amplitude. There is currently sufficient evidence that may allow the inclusion of NMES to conventional exercise therapy, especially in cases where patients cannot actively participate in exercise because of pain, immobilization or arthrogenic muscle inhibition. It is necessary to conduct additional studies in order to develop standardized parameter protocols across various diseases.

Keywords: Neuromuscular electrical stimulation (NMES); musculoskeletal; rehabilitation; exercise therapy.

1. Introduction

Musculoskeletal diseases are a significant source of pain, disability and decreased quality of life across the globe. Among them are osteoarthritis, injuries of ligaments, and peri-articular pain syndrome. It is estimated that KOA afflicts some 30 million U.S. adults and costs the national health care system over \$16.5 billion in annual expenses [1]. The lack of muscle strength following ACL injury may remain present over years and facilitate faster rate of KOA development [2]. Annual prevalence of PFP in the general adult population is 23 percent[3]. Exercise therapy is the first-line treatment of most musculoskeletal problems. It enhances the neuromuscular coordination, muscle strengthening and joint stabilization. Nonetheless, there are various challenges associated with clinical practice. Patients may not be able to participate in early active high-intensity training because of pain or surgical immobilization. Arthrogenic muscle inhibition thwarts voluntary activation and thus normal training cannot achieve sufficient intensity. Long-term benefits of exercise therapy are frequently lost because poor adherence to the program in the long term reduces their effectiveness. These constraints have driven the investigation into the use of adjunct physical therapy modalities.

NMES is a non-invasive method which involves the application of low-or medium-frequency currents through surface electrodes. Such currents stimulate motor nerves and produce muscle contractions. NMES can be used to preserve or boost muscle strength in those cases where patients are unable to contract voluntarily [4]. As a supplement or an alternate to active exercise, NMES is growing to be one of the more popular interventions in multimodal rehabilitation regimens. Nonetheless, its additional benefits have been shown to be inconsistent. Its effectiveness is largely based on stimulation parameters, type of illness, and severity of combined treatment. There is currently no universal standard guideline on clinical practice. The current review provides an overview of available evidence regarding NMES incorporation into the most commonly encountered musculoskeletal conditions and presents the results of its impact on pain, strength, and function as well as methods of optimizing parameters.

Contrary to earlier reviews that considered only one particular condition, this review adopts a cross-disease approach to generalize the use of NMES in various musculoskeletal conditions, aiming to identify shared treatment patterns and disorder-specific aspects. Besides, a time-dependent model of NMES implementation is suggested, dividing early post-surgical intervention (starting within 48 hours to 1 week) and chronic condition treatment (with a duration of more than 4 weeks), which might allow cli-

nicians to have a more defined decision-making schedule. Moreover, some of the important research gaps are also indicated, such as no standardized cross-disease measures and poor evidence on long-term structural effects (e.g., tendon morphology or regeneration), which can give clear guidelines to future research.

2. Physiological Basis and Parameters of NMES

2.1 Physiological Basis

NMES uses the surface electrodes to apply electrical currents to the neuromuscular system, which causes depolarization of motor nerve axons, which cause muscle contraction. In contrast to voluntary contraction, where slow-twitch type I fibers are recruited first and fast-twitch type II fibers second (Henneman size principle), NMES preferentially activates type II fast-twitch fibers close to the electrodes [4]. Large motor units are normally not recruited at low intensities in voluntary contractions. NMES does not follow this sequence but engages them directly. That is why it can be explained by why adding NMES to low-intensity exercise results in additional strength gains. In addition to the direct activation of motor nerve, NMES may also activate motor neurons in an indirect way through the stimulation of afferent nerve fibres. Papavasiliou et al. conducted a systematic review of the 87 NMES protocols aimed at afferent pathways and showed that high intensity, wide-pulse ($\geq 0.5\text{ms}$), high frequency ($\geq 80\text{Hz}$) stimulation is more likely to stimulate Ia sensory fibers. This excitation enhances motor neuron excitation through spinal reflex circuits, which is the primary mechanism behind the wide-pulse high-frequency (WPHF) NMES [5]. As compared with standard low-frequency transcutaneous electrical nerve stimulation (TENS) which is primarily intended to produce analgesic effects, WPHF-NMES can generate constant motor output at much lower stimulation intensities and is less fatiguing on muscles than direct motor excitation. It offers a novel method of treating neuromuscular dysfunction.

2.2 Stimulation Parameters

Therapeutic results are directly affected by parameter settings. The Novak et al. suggested standardized parameter suggestions of KOA patients to enhance strength and relieve pain: the frequency should be 50-75 Hz, the pulse duration 200-400 μs , and the duration of each session must be at least 20 minutes [6]. Torque output is linearly related to frequency but increased frequency leads to quicker fatigue. Wider pulses (e.g., 400 μs) facilitate acti-

vation of larger muscle areas. Current intensity should be adjusted to the maximal tolerable level to maximize motor unit recruitment. Medium-frequency interferential current (IFC) (4000 Hz carrier, 50 Hz beat frequency) offers better skin penetration and patient comfort than low-frequency currents, making it a clinically promising mode [1]. Conley et al.'s systematic review further defined parameters for post-knee surgery: start within the first 2 weeks, frequency ≥ 50 Hz, maximal tolerable intensity, biphasic waveform, large electrodes (≥ 40 cm²), and duty cycle 1:2-1:3 [7]. Additional parameters from TKA studies include frequency 30-100 Hz, intensity 100-120 mA, electrode size 100-200 cm², 1-2 times daily, for 4-6 weeks. Notably, Cavalcante et al.'s recent meta-analysis demonstrated that asynchronous current delivery generates significantly greater isometric torque than traditional synchronous mode ($P < 0.01$), with markedly less fatigue. This finding offers a new direction for parameter optimization – current timing itself may be a modifiable therapeutic variable. However, these parameter recommendations derive from single or a few studies in specific diseases, and there is currently no unified standard based on multi-disease comparisons. Further research is needed to clarify these issues.

3. Application of NMES in Specific Diseases

3.1 Knee Osteoarthritis (KOA)

KOA is characterized by cartilage degeneration and chronic pain. Quadriceps weakness is both a consequence and a driver of disease progression. One RCT enrolled 75 KOA patients (Kellgren-Lawrence grades II-III, aged 50-75) and divided them into NMES group, exercise group, and combined group (exercise + NMES). After 12 weeks, the combined group exhibited improvements in flexion range of motion (FROM) (FROM from 120.5° to 128.5°). Vastus medialis oblique (VMO) thickness increased from 15.0 mm to 16.4 mm (post-intervention, +1.4 mm) and further to 18.2 mm at follow-up (+3.2 mm vs. baseline). WOMAC total score decreased from 46.9 to 38.7 (post-intervention, -8.2) and further to 27.7 at follow-up (-19.2 vs. baseline). The NMES group performed better in the Timed Up and Go (TUG) (from 9.7s to 7.7s) and the 6-minute walk test (6MWT) (from 442m to 549m). VAS pain score decreased from 5.10 to 3.18 (post-intervention, -1.92) and further to 1.78 at follow-up (-3.32 vs. baseline, $P = 0.022$). Pain relief was significantly superior to that of other groups [1]. These data suggest that combined intervention produces synergistic effects on muscle strength, structure,

and function. This conclusion was further confirmed in Novak et al.'s systematic review – NMES is the most effective electrical stimulation modality for KOA, and its efficacy is maximized when combined with strength training [6].

3.2 Chronic Pain Conditions

Chronic pain is a common complaint in musculoskeletal disorders. PFP is more prevalent in active populations. CLBP is highly prevalent in middle-aged and older adults and those engaged in heavy physical labor. Both are characterized by persistent pain and functional limitation. One meta-analysis (9 RCTs, 337 patients) evaluated the efficacy of NMES combined with exercise for PFP and revealed that NMES plus exercise significantly improved pain ($MD = -0.37$, 95%CI: -0.64 to -0.10), function ($MD = 4.76$, 95%CI: 2.08 to 6.84), and strength ($SMD = 0.55$, 95%CI: 0.24 to 0.87). Subgroup analysis indicated that significance was only reached when intervention duration exceeded 4 weeks ($MD = -0.28$, 95%CI: -0.54 to -0.02, $P = 0.03$), suggesting that a minimum treatment period of 1 month is clinically required [8]. Another meta-analysis (45 RCTs, 2023 patients with patellofemoral pain) further verified that NMES plus exercise was superior to exercise alone for short-term (< 3 months) pain relief ($SMD = -0.27$, 95%CI: -0.53 to -0.02), although the certainty of evidence was very low [3].

CLBP is characterized by lumbar multifidus atrophy and dysfunction. Restoring control of the deep stabilizing muscles is a core rehabilitation goal. One controlled study divided 40 CLBP patients into an exercise group and an exercise-plus-NMES group. NMES intensity was individualized in accordance with ultrasound monitoring to obtain a palpable muscle contraction. In 5 weeks, the combined group was found to have significantly higher changes than the exercise group in left multifidus thickness (2.84 to 3.04 cm, +0.20 cm, $P < 0.001$) and movement-related pain (NRS-movement 6.40 to 2.30, -4.10, $P < 0.001$) [9]. One more pilot study in elderly subjects ($n = 31$) revealed that the improvement in function (6 months) of the TMT+NMES group was 73.9 percent and 56.7 percent in the passive control group, and the difference between groups was 17.2 percent (95 percent CI: 5.87-28.60). The result verified the ability and possible effectiveness of NMES-assisted trunk training in elderly CLBP patients [10].

3.3 Post-operative Rehabilitation

The central challenge of post-operative rehabilitation is that the surgical location should be safeguarded as soon as possible but passive exercise delays may lead to muscle

atrophy and arthrogenic inhibition. In this section there are three surgical procedures with different anatomy, but all outcomes demonstrate that NMES can successfully maintain the muscle power and contribute to functional recovery early in the post-operative phase, which is why this is an essential solution to the dilemma.

Quadriceps inhibition and atrophy remain the two significant obstacles to functional recovery after total knee arthroplasty. The main problem is that early joint protection is needed, but activity later on leads to greater strength loss. A meta-analysis (6 RCTs, 496 patients) showed that the NMES group performed better than controls in TUG (mean improvement ~ 1.5 s), stair climbing test (SCT) (improvement ~ 2 -3 s) and 6MWT (improvement ~ 30 -50m). These advantages followed a significant time gradient - they were the highest at 4-12 weeks after surgery and slowly decreased after 12 weeks [11]. The so-called "window period" indicates that NMES is used as a solution when early active exercise is not enough, but not as a substitute to following progressive strength training. An RCT with 200 patients demonstrated that beginning NMES at 4 weeks after surgery did not contribute to substantial additional strength gains [12]. Several studies point out that the timing of initiating NMES at 48 hours post-surgery is much more important in reversing initial strength loss. Also, cell-level analysis indicated that the NMES group strength normalized to 0.68 N-m/kg at 2 weeks post-surgery, whereas the usual rehabilitation group was 0.49 N-m/kg (+39, $P=0.039$). Cross-sectional area of myosin heavy chain (MHC) IIA fibers was greater in the NMES group ($P=0.005$), and MHC IIA/IIX fibers were also bigger ($P=0.002$) whereas MHC I fibers were not different ($P=0.581$). It is confirmed that NMES preserves fast-twitch muscle fibers, which is a major factor in the maintenance of medium-term strength [13].

The arthrogenic muscle inhibition after the ACL reconstruction also does not allow patients to completely activate the quadriceps. Traditional training cannot address this problem. Two studies investigated various forms of NMES intervention at different levels. At cellular level, Toth et al. did sham-controlled RCT where NMES was administered immediately after injury and extended to 3 weeks post-surgery. The biopsy done 3 weeks post-surgery indicated that NMES significantly decreased the atrophy of fast-twitch MHC II fibres ($P<0.01$) and maintained the contractile properties of slow-twitch MHC I fibres (the maximum shortening velocity increased by some 8 percent, $P<0.01$). Nevertheless, whole-muscle strength did not differ across groups at 6 months. It indicates that the initial cellular protection did not lead to long-term benefit as further rehabilitation was the same [14]. At functional level, Labanca et al. combined NMES with functional

exercise (sit-to-stand, squat, step-up) on 15 days post-surgery and maintained it up to 6 weeks. It was found that the quadriceps isometric strength of the NMES group was 32 percent greater at 60 days post-surgery compared to controls ($P<0.05$) and this superiority continued up to 1 year. There were no differences in tendon morphology, indicating that there was more neural adaptation than structural change [2].

Shoulder surgery rehabilitation is in a similar situation: early fixation of repaired tissues limits voluntary movement, and it must be noted that immobilization is always associated with atrophy of the deltoid muscle and loss of function. Two RCTs examined NMES from different angles. The first applied NMES to the deltoid for 4 weeks after reverse total shoulder arthroplasty. At 3 months post-surgery, the NMES group had significantly better external rotation range (36° vs 29° , $P=0.003$) and strength (4.8 kg vs 3.8 kg, $P<0.002$) than controls, but subjective functional scores (ASES, Constant) and deltoid thickness showed no difference [15]. This may be because the altered deltoid mechanics after reverse arthroplasty cannot be reversed by short-term electrical stimulation alone. The second study implemented 6-week home-based NMES after arthroscopic rotator cuff repair. At 6 weeks, the NMES group had significantly better Constant-Murley scores (CMS) (76.10 vs 71.22, $P=0.032$), forward flexion range (151.7° vs 141.8° , $P=0.003$), deltoid thickness (1.02 mm vs 0.91 mm, $P<0.001$), and lower Tampa Scale for Kinesiophobia (TSK) scores (31.06 vs 35.42, $P=0.020$) than the sham group [16]. Notably, at 3 months post-surgery, except for abduction strength (42.3 N vs 35.9 N, $P=0.046$), all other differences disappeared. This indicates that NMES mainly accelerates early recovery rather than altering long-term outcomes.

3.4 Other Conditions

For ICU-acquired weakness (ICUAW), a systematic review (8 RCTs, 172 patients) revealed that NMES in the ICU effectively prevented acquired weakness. Five studies reported strength improvements. One demonstrated a large effect size ($d=1.44$). Compliance was 81-100%, and no adverse events occurred [4]. A multicenter RCT (200 patients) found no significant improvement in overall walking distance for intermittent claudication. However, subgroup analysis indicated that patients with longer baseline walking distance (milder disease) could benefit from NMES ($P=0.02$) [17]. In sarcopenia, Teschler et al.'s three-arm RCT showed that 4 weeks of electromyostimulation (EMS) combined with standard rehabilitation increased knee extensor strength by 10.4% compared to rehabilitation alone ($P=0.008$). The chair rise test also

improved significantly ($P=0.001$). No adverse events occurred. This suggests NMES has potential application in age-related muscle atrophy [18].

It is worth noting that most of the above studies employed a "NMES + exercise vs. exercise alone" design, rather than "NMES vs. other". This makes it difficult to fully isolate the independent effect of NMES. However, the incremental benefit over standard rehabilitation has received preliminary support.

4. Conclusion

NMES demonstrates potential for improving pain, strength, or function in KOA, PFP, ACL reconstruction, TKA, CLBP, rotator cuff repair, ICU-acquired weakness, and sarcopenia. Based on existing evidence, the following core findings can be derived. First, timing of initiation is critical – starting within 48 hours to 1 week post-surgery yields the most pronounced effects. For chronic pain conditions, treatment lasting more than 4 weeks is needed to achieve meaningful improvement. Second, the added benefit of NMES is inversely related to baseline exercise intensity. When conventional rehabilitation is already of high intensity, the additional benefit of NMES is limited. When exercise is restricted by pain or immobilization, NMES offers unique value in filling the training gap.

This review has some limitations. Firstly, in the original studies that were included there was great heterogeneity in the parameters of NMES (frequency, pulse duration, intensity, duration of treatment) which makes it difficult to compare different studies directly. Secondly, most of the studies incorporated into the review were based on the idea of NMES+exercise versus exercise only design instead of sham-controlled designs so that it is challenging to determine the independent effect of NMES independently of expectation effects. Thirdly, the amount of studies on particular conditions (e.g., rotator cuff repair) is still too low, and most of the RCTs include small numbers of participants and have limited follow-up time (usually not more than 6 months), which restricts making statements about long-term effectiveness.

Future research should focus on developing disease-specific standardized parameter protocols, especially differentiated settings for different muscle groups (fast- vs. slow-twitch dominant, superficial vs. deep). High-quality randomized controlled trials with longer follow-up (≥ 1 year) are needed to clarify NMES effects on long-term structural changes such as fatty infiltration and tendon remodeling. Personalized precision rehabilitation should be advanced by using wearable devices and artificial intelligence to dynamically adjust parameters, moving NMES from fixed protocols to adaptive ones. The cellular and

molecular mechanisms of NMES (including fiber type transformation, satellite cell activation, and neural plasticity) also require further investigation.

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