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Who's Afraid of Electrical Stimulation? Let's Revisit the Application of NMES at the Knee

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Abstract

BACKGROUND: Restoring quadriceps strength is essential for successful rehabilitation of knee injuries, but many athletes return to their previous activity with persisting muscle weakness. Strong evidence supports using neuromuscular electrical stimulation (NMES) to improve quadriceps strength; however, there is a lack of widespread clinical implementation. We believe there is a critical need to provide clinical approaches that promote using NMES to improve patients' quadriceps strength and ensuring clinicians provide high-value rehabilitation care.

CLINICAL QUESTION: What is best practice when using NMES to facilitate strength after injury, what are barriers to its use, and how can they be addressed?

KEY RESULTS: We discuss the low clinical implementation of NMES, perceived barriers to using NMES, and provide recommendations for setup and dosage parameters for effective use of NMES.

CLINICAL APPLICATION: We aim for this commentary, with accompanying videos, to serve as a resource for clinicians who are using commercially available NMES units in clinical practice.

Keywords

anterior cruciate ligament; inhibition; physical therapy; quadriceps strength; rehabilitation

After knee injury and surgery, poor outcomes are common, and they limit return to full activity.²² Quadriceps inhibition and weakness are ubiquitous and persist from early after

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injury and surgery through the time of return to sport. Quadriceps inhibition (ie, arthrogenic muscle inhibition, activation failure) is difficulty achieving full muscle activation/contraction after knee joint injury and/or surgery, and can persist long term.^{23,33} Weak quadriceps at the time of return to sport is a predictor of knee reinjury²¹ and a risk factor for developing clinical and radiographic knee osteoarthritis.^{1,30} At return to sports, quadriceps strength is associated with asymmetric knee mechanics during single-leg landing tasks.³¹ Meeting quadriceps strength cutoffs at the time of returning to sport is critical.⁶ Yet despite clear evidence, athletes very often do not meet the cut-off values.^{19,38} This relationship between quadriceps weakness and postoperative outcomes is not confined to ACL injury—patients have problems recovering strength after other common knee surgeries and impairments (including total knee arthroplasty), where restoring quadriceps strength is also a key postoperative goal.⁴² Adequately addressing quadriceps activation and strength is vital for successful rehabilitation outcomes after knee injury or surgery.

Where Does NMES Fit in?

Neuromuscular electrical stimulation (NMES) combats muscle inhibition by facilitating recruitment of muscle that may be inhibited by pain or effusion. It overcomes impaired muscle activation by increasing motor unit recruitment and rate coding (motor unit firing rate).³ Literature from as far back as the 1990s supports the use of NMES³⁷; however, in recent studies, NMES dosage parameters have been insufficient (ie, not dosed to sufficient amplitudes or with a quantifiable target), washing out the clear effects of NMES and confusing the clinical community. In many studies, NMES was not dosed to even 50% of the patient's maximal voluntary isometric contraction (MVIC).^{11,13,24,26,34} While many of these studies are from 20+ years ago, they emphasize the need to use appropriate dosing parameters to achieve the intended effect of NMES. Many studies used electrical stimulators that cannot produce adequate electrical stimulation amplitude to the muscle, leading to underdosed treatment.

In the 2017 clinical practice guidelines for Knee Stability and Movement Coordination Impairments: Knee Ligament Sprain, NMES was graded an “A,” meaning strong evidence.²⁷ Some of the earliest work done on NMES was a study measuring the effects of high-intensity NMES vs low-intensity NMES in addition to ongoing rehabilitation. This study found that high-intensity dosage was necessary to recover quadriceps muscle force production in the early phases of rehabilitation.³⁷ Similar work with 110 patients who all participated in an intensive strengthening program compared the addition of high-intensity NMES to high-level volitional exercise and to the addition of low-intensity NMES. The results corroborated that high-intensity NMES had the best outcomes, followed by high-level volitional exercise; the low-intensity NMES group lagged behind.³⁶ In another foundational study,¹⁶ a similar high-intensity NMES protocol was tested, this time using a modified approach for patients who received patellar tendon grafts for ACL reconstruction and had anterior knee pain. Again, the NMES group had more quadriceps strength gains after 12 weeks of treatment compared to the standard-of-care group, and a greater proportion of individuals who ultimately achieved the clinical criteria to advance to agility training at 16 weeks.¹⁶

Since those early studies, many reviews have supported the same point: high-intensity NMES plus traditional rehabilitation and strengthening programs is more effective in restoring quadriceps muscle strength than traditional rehabilitation alone, and must be implemented early and frequently after injury or surgery to deliver best outcomes.^{4,7,17,32,41} With clear evidence of the benefits of NMES for restoring quadriceps strength after knee injuries, it is a disservice to patients if clinicians choose not to incorporate NMES into standard rehabilitation practice.

In a recent survey of 54 physical therapists (n = 49) and physical therapist assistants (n = 5) in New Jersey, only 52% were aware of the clinical practice guideline giving NMES an “A” rating and only 56% used NMES for post-ACL injury rehabilitation in the last 3 years.²⁹ Of the 56% who used NMES, it is also unknown what proportion of therapists dosed NMES at a therapeutic level (discussed later), meaning the implementation of NMES at appropriate dose is likely even lower.

CLINICAL QUESTIONS

Why is the Effectiveness of NMES Questioned?

Potential reasons for lack of appropriate implementation may be the (1) absence of NMES being included in post-operative protocols, (2) lack of knowledge on appropriate dosing, and (3) addition of another modality when hands-on time with patients is at a premium and pressure for further reduction in one-on-one time with each patient. When surveying the use of NMES in other patient populations, similar barriers are seen such as insufficient knowledge about prescribing NMES,^{2,15} low comfort level,⁴⁰ and time.^{2,40} NMES should be initiated immediately when physical therapists identify quadriceps weakness and should be dosed to a minimum of 50% of the patient’s isometric MVIC.²⁵

At the high NMES dosage required for muscle strengthening, the stimulus is always uncomfortable but can be minimized with appropriate use of skin preparation and electrodes (see the Electrodes section). Clinicians, while being empathetic, should work to find strategies with their patients to dose NMES using what will be an uncomfortable level of current to achieve a therapeutic muscle contraction dose. Patient education during this stage is critical, including a thorough explanation of the process and the benefits of NMES, showing graphs of each contraction for feedback, and getting to know the patient to communicate effectively. Patients have various coping strategies to tolerate pain. Some use techniques like deep breathing, whereas others find strategies that provide detail about the procedures help.¹⁰ One patient may prefer to use biofeedback via the output from the dynamometer to best reach their target, but another may prefer to simply close their eyes and listen to music. After thorough education on maximizing torque output, allowing for autonomy with dosing by handing the patient their stimulator may also allow for superior outcomes. We believe that the clinician in charge should control the output during early stages until the patient understands what the therapeutic dose (minimum 50% MVIC) feels like. While some trial and error is inevitable with each patient, finding the patient’s preferred coping strategies will help to achieve therapeutic dosing.⁹

Clinicians must retest MVIC using validated methods³⁹ every visit to properly dose NMES for strengthening. Achieving appropriate therapeutic dosage is the key to elicit improvements in quadriceps strength. There are several clinical techniques to assess MVIC. If there is no access to an isokinetic dynamometer, a handheld dynamometer (HHD) affixed isometrically is the next best method, and if there is no access to a HHD, then a 1-repetition-maximum testing of knee extension is the next best way to assess MVIC (see SUPPLEMENTAL VIDEO for the setup: <https://www.youtube.com/watch?v=hGRqUMQDoWk>).³⁵

Clinicians may also be wary of implementing NMES because of the time required to set up and appropriately dose a treatment. We argue, and evidence supports,^{16,17,37} that this time is well spent during a treatment session because of the effectiveness of NMES in improving strength. Extra time spent on NMES during individual treatment sessions supersedes the many visits of PT that would be wasted with insufficient dosing of quadriceps strength exercises.

What Parameters Do I Use?

Specific parameters may be adjusted for patient comfort; however, NMES should be applied with at least 400-microsecond pulse width at 50 to 75 pulses per second for pulsed current (or 1000 Hz AC (aka Australian) or 2000 Hz AC (aka Russian) burst modulated at 50 to 75 bursts per second) with a 2-second ramp-up, 10-second contraction (for a total of 12 seconds “on” time), and 50-second rest to mitigate fatigue.²⁰ Strength of contraction increases with increasing frequency, but at higher frequencies, motor unit fatigue rapidly occurs.¹⁴ The force frequency curve of human quadriceps shows the inflection point occurs between 50 to 80 pulses per second.⁵ Again, the muscle contraction elicited by the electrical stimulation should produce a force of at least 50% of the MVIC, and more is better. The NMES is *not* superimposed on a volitional contraction of the quadriceps during this treatment.

While current clinical practice guidelines support NMES in rehabilitation,²⁹ there is uncertainty about the dose-response relationship. Specifically, the ideal timing and amount of NMES are unclear. In healthy individuals, higher-intensity training (50% of force) yielded significantly better results than lower-intensity training.²⁵ In individuals who had torn their ACL, higher-intensity training (~40% of force of the uninjured limb) was associated with better recovery.³⁷ Though no studies have comprehensively assessed dose-response of NMES, the higher the intensity, the more substantive the quadriceps strength recovery.^{8,28}

Patient and surgical site safety is another concern for clinicians when implementing NMES postoperatively. NMES is safe⁴³ to begin immediately post-operatively as it is dosed based on the patient’s available isometric MVIC and therefore does not supersede the patient’s possible force output. Where a primary surgery has taken place (e.g., quadriceps and patellar tendon repairs, patellar re-alignment surgeries) appropriate tissue healing and loading need to take place prior to MVIC and NMES application, which is often 16–20 weeks or earlier phases with surgeon approval and altered pad placement and modified knee angles.

Electrodes

Using larger electrodes provides an electrical field that crosses the motor points¹⁸ of all 4 heads of the quadriceps, while being more comfortable because of the larger surface area for the current and while simultaneously improving force production. We suggest using large 3 × 5-inch electrodes (FIGURE). Prior to placing the electrode, prepare the skin adequately for treatment. Clean the skin with mild soap and water to improve contact of the electrode, reduce skin impedance, and evenly distribute the current. Avoid isopropyl alcohol wipes to prevent drying of the skin, which increases skin impedance. To assist in appropriate dosage and implementation of NMES, we have included a video as a supplemental file that summarizes clinically feasible setups for NMES, plus dosage and progression (See SUPPLEMENTAL VIDEO and Written Guide to NMES in SUPPLEMENTAL FILE 1).

To ensure safety when using NMES, check that the skin is intact prior to preparing for the electrodes, continue to monitor the skin for signs of irritation, ensure full contact of the electrodes with the skin, and adjust stimulus parameters with caution.¹² Contraindications and precautions of NMES are consistent with those of any electrophysical agents,¹² including active deep vein thrombosis, damaged skin, impaired circulation, infection, and malignancy.

Which Electrical Stimulators Are Best for My Clinic?

We reached out to 36 companies who sell electrical stimulators asking for sample electrical stimulators to test on behalf of the broader, international clinician population (See letter in SUPPLEMENTAL FILE 2). Nine companies responded with 5 of the 9 companies providing us with sample electrical stimulators to test. We tested each of the 5 electrical stimulators on 5 healthy members of our lab with each member starting the test on a separate electrical stimulator to account for the effects of fatigue on output. Each electrical stimulator was set up with recommended parameters as previously described, or the closest possible parameters if the recommended parameters were unable to be achieved (TABLE). Three-by-five-inch electrodes were used, and the position of electrodes was held consistent for each electrical stimulator tested.

We first tested each member's MVIC on our dynamometer, then tested the torque output from each electrical stimulator's 50% capacity (ie, if 100 mA is the max output from the electrical stimulator, 50 mA was used), then followed that by torque output from the maximum tolerated stimulation. Each member was given up to three 10-second contraction cycles to achieve their highest tolerance to the electrical stimulators tested. During testing, it was clear that even with an understanding of what NMES entails and experience using NMES with patients, it was difficult to achieve the correct dosage from some team members. This, again, emphasizes the importance of patient education and buy-in to achieve a therapeutic dose using NMES.

The *Chattanooga Continuum* achieved the highest mean output at tolerance. One member maxed out the electrical stimulator and 4/5 members achieved dosages above 50% MVIC. The one who was unable to achieve 50% MVIC reached 49% MVIC. The *InTENSity Select Combo II* achieved the second highest mean output at tolerance. Again, 1 member maxed

out the electrical stimulator, and 3 tolerated above 50% MVIC. The *Longest LGT-231* also had 3/5 members meeting therapeutic dose but with slightly lower mean output compared to the *Select Combo II*. The only wall (plug in) electrical stimulator in our list, the *Dynatronics Solaris 709 Plus*, achieved the highest output at 50% of the electrical stimulator's maximum capacity. This was the only electrical stimulator that no member was able to max out the current setting. This electrical stimulator was also the most uncomfortable, and 3/5 members were unable to tolerate beyond 50% capacity (50 mA) of the current setting on the electrical stimulator (TABLE).

The *Chattanooga Continuum* (the electrical stimulator featured in our instructional video) was the electrical stimulator that allowed almost all members to achieve a therapeutic dose. The *Solaris 709 Plus* may be considered for NMES in the clinic for patients who have high tolerance to stimulation or those who do not reach therapeutic dose on the highest settings using the continuum. This only wall-current unit on the list was the stimulator that provided the highest amount of torque output at 50% capacity of the stimulator, suggesting that this stimulator may provide the most powerful contraction if higher current settings are tolerated.

While our testing was completed with healthy individuals, we were assessing the ability of the units to reach a therapeutic dose. The tolerance thresholds and testing methods may differ in a clinical sample. However, we are confident similar performance of the units will transfer to patients.

SUMMARY

USING NMES TO AUGMENT QUADRICEPS strength training in patients after knee injury and surgery is critical to improving functional outcomes and reducing the risk of reinjury. Setting up NMES with appropriate parameters and dosage to maximum tolerance at each visit is essential for ensuring patients are achieving the optimal treatment effect. With the use of NMES at an early postinjury timepoint, clinicians can attenuate the detrimental long-term effects of quadriceps weakness and inhibition in patients after knee injuries.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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KEY POINTS**FINDINGS:**

Neuromuscular electrical stimulation (NMES) is effective for augmenting quadriceps strength in patients after knee injury and surgery when applied with appropriate dosage and parameters.

IMPLICATIONS:

NMES must be dosed to at least 50% of the patient's maximal voluntary isometric contraction (MVIC) from the same-day visit, and the electrodes should be at least 3 × 5 inches for maximal patient comfort. Clinicians should consider patients' perception of pain and discomfort and find the best coping mechanism to maximize use of electrical stimulation.

CAUTION:

Electrical stimulators may vary based on comfort, which affects torque output. It is important to find the best balance between achieving an adequate torque output and being tolerated by patients.



FIGURE.
Example placement of electrodes over quadriceps motor points.

TABLE 1.

Comparison between commercially available electrical stimulators.

	Participant number	1	2	3	4	5
Participant characteristics	Sex	female	male	male	female	female
	Age (years)	41	30	27	27	23
	Height (m)	162.6	180.0	185.0	170.2	170.2
	Weight (kg)	65.8	98.8	82.1	97.9	82.6
	MVIC (Nm)	141	349	357	280	200
Chattanooga: Continuum Symmetric biphasic current Current: 0–100 mA Frequency: 75 Hz Pulse width: 400 µs Contraction time: 10 sec Relaxation time: 50 sec Ramp: 2 sec	50% Output (%MVIC)	45	13	5	6	54
	Max tolerance (mA)	66	89	68	100*	70
	Output at tolerance (%MVIC)	92	49	58	58	84
InTENSity: Select Combo II Symmetric biphasic current Current: 0–100 mA Frequency: 50 Hz ⁺ Pulse width: 400 µs Contraction time: 10 sec Relaxation time: 50 sec Ramp: 2 sec	50% Output (%MVIC)	38	22	0	2	51
	Max tolerance (mA)	64	72	79	100*	81
	Output at tolerance (%MVIC)	87	36	60	29	86
Saebo: SaeboStim Pro Symmetric biphasic current Current: 0–60 mA Frequency: 75 Hz Pulse width: 350 µs ⁺ Contraction time: 10 sec Relaxation time: 10 sec ⁺ Ramp: n/a ⁺	50% Output (%MVIC)	0	0	0	0	0
	Max tolerance (mA)	60*	60*	60*	60*	60*
	Output at tolerance (%MVIC)	43	20	13	5	58
Longest: LGT-231 Symmetric biphasic current Current: 0–100 mA Frequency: 75 Hz Pulse width: 400 µs Contraction time: 10 sec Relaxation time: 50 sec Ramp: 2 sec	50% Output (%MVIC)	23	17	4	9	23
	Max tolerance (mA)	56	68	82	98	88
	Output at tolerance (%MVIC)	39	33	66	56	86
Dynatronics: Solaris 709 Plus Dymmetric bphasic current Current: 0–100 mA Frequency: 75 Hz Pulse width: 400 µs Contraction time: 10 sec Relaxation time: 50 sec Ramp: 2 sec	50% Output (%MVIC)	47	34	28	17	77
	Max tolerance (mA)	50	50	50	78	56
	Output at tolerance (%MVIC)	47	34	28	50	83

Green = met therapeutic dose (> 50% MVIC), Yellow = within 10% of therapeutic dose (> 40% MVIC)

* = Highest current output achieved on stimulator

⁺ = Parameters that did not meet requirements