A Comparison of Neuromuscular Electrical Stimulation Parameters for Postoperative Quadriceps Strength in Patients After Knee Surgery: A Systematic Review

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Context: Postoperative quadriceps strength weakness after knee surgery is a persistent issue patients and health care providers encounter.

Objective: To investigate the effect of neuromuscular electrical stimulation (NMES) parameters on quadriceps strength after knee surgery.

Data Sources: CINAHL, MEDLINE, SPORTDiscus, and PubMed were systematically searched in December 2018.

Study Selection: Studies were excluded if they did not assess quadriceps strength or if they failed to report the NMES parameters or quadriceps strength values. Additionally, studies that applied NMES to numerous muscle groups or simultaneously with other modalities/treatments were excluded. Study quality was assessed with the Physiotherapy Evidence Database (PEDro) scale for randomized controlled trials.

Study Design: Systematic review.

Level of Evidence: Level 1.

Data Extraction: Treatment parameters for each NMES treatment was extracted for comparison. Quadriceps strength means and standard deviations were extracted and utilized to calculate Hedge *g* effect sizes with 95% CIs.

Results: Eight RCTs were included with an average Physiotherapy Evidence Database scale score of 5 ± 2. Hedge *g* effect sizes ranged from small (−0.37; 95% CI, −1.00 to 0.25) to large (1.13; 95% CI, 0.49 to 1.77). Based on the Strength of Recommendation Taxonomy Quality of Evidence table, the majority of the studies included were low quality RCTs categorized as level 2: limited quality patient-oriented evidence.

Conclusion: Because of inconsistent evidence among studies, grade B evidence exists to support the use of NMES to aid in the recovery of quadriceps strength after knee surgery. Based on the parameters utilized by studies demonstrating optimal treatment effects, it is recommended to implement NMES treatment during the first 2 postoperative weeks at a frequency of ≥50 Hz, at maximum tolerable intensity, with a biphasic current, with large electrodes and a duty cycle ratio of 1:2 to 1:3 (2- to 3-second ramp).

Keywords: anterior cruciate ligament; total knee arthroplasty; meniscectomy; quadriceps impairment

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Knee pathologies such as anterior cruciate ligament (ACL) tears, meniscal injuries, and chondral injuries are frequently treated with surgical interventions to address symptoms or the overall health of the joint. Subsequent quadriceps weakness and poor limb symmetry indices are common consequences after knee surgery and have been observed to persist for years after surgery.[45,55,68] Furthermore, relationships between quadriceps strength and functional performance, such as gait, have been reported.[37] Subsequently, long-term consequences, such as osteoarthritis, are a concern for patients with quadriceps strength deficits.[26,39,50] Addressing postoperative quadriceps weakness is advantageous for positive short- and long-term patient outcomes.

Neuromuscular electrical stimulation (NMES) is one therapeutic modality utilized to improve postoperative quadriceps weakness. Neuromuscular electrical stimulation has demonstrated mixed success as a clinical modality for facilitating strength restoration. After ACL reconstruction specifically, 4- to 6-week bouts of NMES have been observed to assist in the recovery of quadriceps strength and functional performance as compared with rehabilitation without NMES.[72,74] However, other ACL-related studies have reported no advantage in postoperative strength from NMES interventions implemented within similar time frames.[35,57] Each of the above studies employed varying treatment parameters likely influencing the outcomes.

Throughout the literature, the NMES parameters reported for treatments vastly differ between studies, possibly due to the sizable amount of NMES parameters available for customization to clinicians. The inconsistency among the parameters has been theorized to contribute to the variable therapeutic effect of NMES on postoperative quadriceps strength previously described.[4,27] Identifying the most effective NMES parameters for recovering quadriceps strength after surgery is essential for optimizing treatment effectiveness. Therefore, the purpose of this review was to investigate the most effective NMES parameters for targeting postoperative quadriceps weakness. The specific parameters investigated included the following: intensity, electrode size, frequency, initiation of treatment, waveform/current, pulse duration, duty cycle, ramp time, knee angle, active or passive muscle contraction, and treatment volume.

METHODS

Searches were performed in December 2018 using the following electronic databases: PubMed, CINAHL, MEDLINE, and SPORTDiscus. Key terms were searched utilizing the search strategy presented in Table 1 and then reviewed for inclusion as outlined in Figure 1. Specifically, search results were exported to an electronic spreadsheet where duplicate references were deleted. The titles of all remaining articles were reviewed to determine study inclusion. If the title alone was not sufficient to determine study eligibility, the abstract was reviewed. The article was retrieved and reviewed in its entirety if a decision regarding inclusion or exclusion was unable to be made from the abstract. Last, a manual search by hand was performed from the references of the final articles included in the study to identify any additional articles.

Selection Criteria

Article inclusion and exclusion criteria were as follows: studies examining NMES treatment benefits classified as a level 2, randomized controlled trials (per The Oxford Center for Evidence-Based Medicine [CEBM] 2011 Levels of Evidence) were included in this review.[51] The CEBM hierarchy ranges from 1 to 5, where a level 5 represents a low level of evidence and a level 1 represents the best level of evidence.[51] English-language and human-based articles reporting randomized controlled trials that measured volitional postoperative quadriceps strength, included a postoperative standard-of-care control group for comparison, and who reported the NMES parameters utilized were eligible for review. Volitional quadriceps strength could be measured through isometric or isokinetic testing. Quadriceps strength means and standard deviations were required to be reported. The standard-of-care control group did not receive any form of a NMES treatment and instead performed postoperative voluntary quadriceps muscle contractions. Studies were excluded if they did not apply an NMES treatment or measure volitional quadriceps strength, applied NMES to other muscles in addition to the quadriceps, applied NMES simultaneously with other modalities/treatments, and/or did not report means and standard deviations. These exclusions were chosen to isolate the effect of an NMES treatment applied directly to the quadriceps on postoperative quadriceps strength. In the instance authors reported adjusted means and standard deviation, the authors were contacted to request the unadjusted means and standard deviation to allow the authors to calculate effect size values.

Assessment of Methodological Quality

Two independent reviewers assessed each articles' eligibility and the quality of evidence. The assessment of the methodological quality was performed utilizing the Physiotherapy Evidence Database (PEDro) scale.[42] The PEDro scale consists of 11 questions; however, only questions 2 to 11, a total of 10 questions, are utilized for the total score calculation. Therefore, the PEDro is a 10-point scale with a high score (10) reflecting a high-quality study. A study with a score greater than or equal to 6 was considered to be of moderate to high quality.[58] Once each reviewer had completed independent assessment of the articles, they met to discuss any disagreements in score. If there was a disagreement between the 2 reviewers, a third reviewer would assess the quality of evidence for the point of disagreement. There were no disagreements between the 2 independent reviewers.

Strength of Recommendation

Strength of recommendation was assessed utilizing the Strength of Recommendation Taxonomy (SORT).[15] The strength of recommendation is evaluated with grades A, B, and C.[15]

Table 1. Systematic search strategy and results

	Search Terms	Results	
		EBSCO Host (1979-2018) CINAHL with Full Text, SPORTDiscus, MEDLINE	PubMed (1966-2018)
#1	Neuromuscular electrical stimulation	2693	7491
#2	Electrical stimulation	63,599	179,630
#3	Clinic* electrical stimulation	749	25,650
#4	Home-based electrical stimulation	72	125
#5	Battery-operated electrical stimulation	6	49
#6	Portable electrical stimulation	34	312
#7	#1 OR #2 OR #3 OR #4 OR #5 OR #6	63,601	179,630
#8	Anterior cruciate ligament	39,391	19,946
#9	ACL	28,166	23,769
#10	Anterior cruciate ligament reconstruction	18,005	10,906
#11	Anterior cruciate ligament revision	659	893
#12	Anterior cruciate ligament repair	941	2282
#13	Anterior cruciate ligament surgery	6946	15,143
#14	Total knee arthroplasty	28,811	28,707
#15	Meniscectomy	4680	2724
#16	Meniscal transplant	84	1121
#17	Meniscal repair	1367	2116
#18	Knee	261,887	155,379
#19	Knee injury	37,547	40,473
#20	Knee surgery	30,817	73,969
#21	#8 OR #9 OR #10 OR #11 OR #12 OR #13 OR #14 OR #15 OR #16 OR #17 OR #18 OR #19 OR #20	278,456	163,687
#22	Rehabilitation	615,335	568,700
#23	Therapy	6,170,174	8,931,528
#24	#22 OR #23	6,582,635	9,020,021
#25	Muscle strength	77,615	60,573
#26	Muscle weakness	29,257	41,915
#27	Quadriceps weakness	978	1364
#28	Quadriceps strength	5222	5051
#29	#25 OR #26 OR #27 OR #28	103,796	97,986
#30	#7 AND #21	2391	2148
#31	#24 AND #30	1477	1342
#32	#29 AND #31	376	310

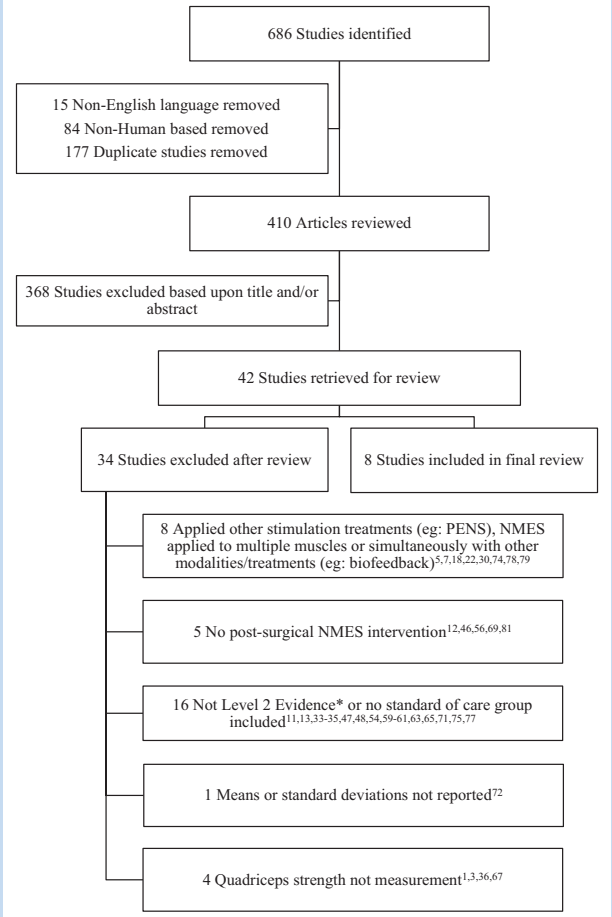


Figure 1. Study selection flowchart for all studies returned in the search. *Based on the Oxford Center for Evidence-Based Medicine (CEBM) 2011. NMES, neuromuscular electrical stimulation; PENS, patterned electrical neuromuscular stimulation.

According to the taxonomy, a *C* is a recommendation founded on case series, consensus, disease-oriented evidence, or expert opinion.[15] A *B* recommendation is given when there is inconsistent or limited quality patient-oriented evidence.[15] Last, a recommendation strength of an *A* is given to consistent good-quality patient-oriented evidence.[15]

Data Extraction

All data were extracted by the primary author. The intervention parameters, administration instructions, and quadriceps strength measures (isometric or isokinetic) were extracted from each study and input into a standardized electronic spreadsheet. The NMES treatment intervention parameters extracted consisted of intensity, electrode size, frequency, initiation of treatment, waveform/current, pulse duration, duty cycle, ramp time, knee angle active or passive muscle contraction, and treatment volume. Subsequently, quadriceps strength means and standard deviations at pre- and posttreatment were extracted. All articles presented group means and standard deviations in text except for 2 articles.[16,38] One article[38] presented means and standard deviations in a graph. The means and standard deviations were extracted from the graph by hand utilizing a digital caliper (Mitutoyo).[49] The other article[16] reported baseline-adjusted means and standard deviations. The posttreatment means and standard deviations were obtained from the article's authors.[16]

Data Analysis

A variable of total active treatment time was calculated. The number of repetitions (*on* portion of the duty cycle) performed in a total duty cycle was computed. This amount was then multiplied by the length of time the contraction was performed to obtain the total time active contractions occurred in a single treatment session. This was then multiplied by the total treatment volume for a total active treatment time over the entire prescribed treatment.

Between group quadriceps strength effect sizes were the primary outcome of interest. Hedges *g* effect size (*g*) and 95% CIs were calculated using all available data to determine the effect of the treatment on quadriceps strength. Effect size calculations were interpreted as small 0.2, moderate 0.5, and large 0.8.[6] Statistically significant treatment effects occurred if the posttreatment confidence interval did not contain zero. An overall effect size was calculated using Comprehensive Meta-Analysis software (Version 3.3.070; Biostat). In a situation where an article had multiple time points or multiple strength assessment, the highest effect size was utilized for the overall effect size calculation. A sensitivity analysis was conducted by calculating an effect size with the lowest effect sizes if an article had multiple time points.

RESULTS

The search strategy resulted in a total of 686 articles from the specified databases (Table 1). A total of 99 non–English language and nonhuman-based studies were excluded through search filters. A total of 177 duplicate articles were excluded and the titles for the remaining 410 articles were reviewed. After reviewing titles and abstracts, an additional 368 articles were excluded. From the remaining 42 articles, a total of 8 studies were included for review[16,17,38,70,76,82-84] and the remaining 34 studies were excluded[1,3,5,7,11-13,18,22,30,33-36,46-48,54,56,59-61,63,65,67,69,71,72,74,75,77-79,81] (Figure 1).

The PEDro scores for the 8 articles ranged from 2 to 7 with an average of 5 (Table 2). All studies lacked 1 or more aspects of blinding, for no study blinded the participants or the treatment administrators (criteria 5 and 6). Additionally, a majority of studies failed to conceal group allocation (criteria 3), blind the assessor of the key outcome (criteria 7), or include or report a baseline group assessment (criteria 4). Examining criterion 4, 5 studies did not provide baseline group assessments.[17,38,70,82,83] Two of the 5 studies[17,70] did not include any baseline information while 3 of the 5 studies[38,82,83] reported baseline

Table 2. Physiotherapy Evidence Database scale (PEDro) Methodological Quality Assessment Scores for each included article[a]

	1[b]	2	3	4	5	6	7	8	9	10	11	Total
Feil et al[16]	×	×	–	×	–	–	×	–	×	×	×	6/10
Fitzgerald et al[17]	×	×	–	–	–	–	×	×	×	×	×	6/10
Lieber et al[38]	×	×	–	–	–	–	–	×	×	×	×	5/10
Sisk et al[70]	×	×	–	–	–	–	–	×	–	×	×	4/10
Stevens-Lapsley[76]	×	×	×	×	–	–	–	×	×	×	×	7/10
Wigerstad-Lossing et al[82]	×	×	–	–	–	–	–	×	×	×	×	5/10
Williams et al[83]	×	×	–	–	–	–	–	–	–	–	×	2/10
Yoshida et al[84]	×	×	×	×	–	–	×	×	–	×	×	7/10

[a]"×" denotes criterion was satisfied, "–" denotes criterion was not satisfied.
[b]Question 1 is not included in the score total.

values but did not report a statistical comparison between groups.

Study Characteristics

Individual study characteristics are presented in Table 3. In 5 articles,[16,17,38,70,82] ACL reconstruction patients were treated, in 2 articles,[76,84] total knee arthroplasty patients were treated, and in 1 article,[83] meniscectomy patients were treated. Quadriceps strength was measured through isometric testing via a dynamometer at various knee angles,[17,38,70,76,82,84] including 30°, 60°, 75°, and/or 90° and with isokinetic testing[16,83] at speeds of 90, 120, 180, 240, and/or 300 deg/s.

Postintervention quadriceps strength measures were reported to statistically improve in 5 of the 8 studies.[16,17,76,82,84] Between group effect sizes calculated for each time point tested and each strength assessment reported in the 8 articles resulted in effect sizes ranging from −0.37 to 1.13 (Figure 2).[16,17,38,70,76,82-84] Moderate to large effect sizes with confidence intervals that did not cross zero were found in 4 studies.[16,76,82,84] The posttreatment confidence intervals for a portion of the calculated effect sizes did cross zero; however, overall there was a favorable trend for the effect of NMES on postoperative quadriceps strength when compared with the standard of care treatment. The overall NMES effect was 0.55 (0.31, 0.75). An effect size of 0.41 (0.21, 0.60) was found in the sensitivity analysis.

Treatment Parameters

The NMES administration setup and treatment parameters can be found in Tables 4 and 5, respectively. There was a high degree of variability in both the amount of NMES treatment parameters reported and the specific parameter settings utilized. Regarding the amount of NMES treatment parameters reported, 4 studies[16,38,83,84] failed to report at least 2 parameters. The parameters commonly absent were current type, waveform shape, and electrode size. Only 4 studies[17,70,76,82] reported all the NMES treatment parameters included in this review.

The varying parameters reported and utilized in each article prevented a meta-analysis from being conducted. Despite the variability, a narrative synthesizing of the parameters from the included studies was conducted. The majority of studies prescribed the intensity to be at a level of maximal tolerance. All but 2 studies[16,38] instructed the patients to continually increase the intensity level over time. One study[84] specifically excluded patients (n = 3) who were unable to tolerate an intensity that produced a visible muscle contraction. A 2-electrode placement generally was implemented, with the exception of Feil et al,[16] who utilized a 4-electrode placement in 1 intervention group (group 1). Predominantly, a frequency of 50 Hz was utilized.[16,38,76,83] When reported, a pulse duration of 250 to 300 μs was most common.[16,38,70,76,82] The NMES treatment was commonly implemented during the first[16,70,76,82] and second[17,84] postoperative weeks. Duty cycle on/off times were inconsistent between studies. When duty cycle times were expressed as a ratio, contraction/relaxation ratios of 1:2[16,38,82,84] and 1:3[70,76,83] were most frequently applied.

DISCUSSION

Regaining quadriceps strength after surgery is a paramount goal during rehabilitation, for quadriceps weakness has been found to increase joint loading[44] and contribute to the development of osteoarthritis.[26] In this review, the effect sizes for NMES on postoperative quadriceps strength, when compared with a control group, ranged from small (−0.37) to large (1.13). While these results align with other reviews supporting NMES[8,27,28] as a positive postoperative treatment directed at regaining quadriceps strength, little focus has been placed on the most effective parameter settings.

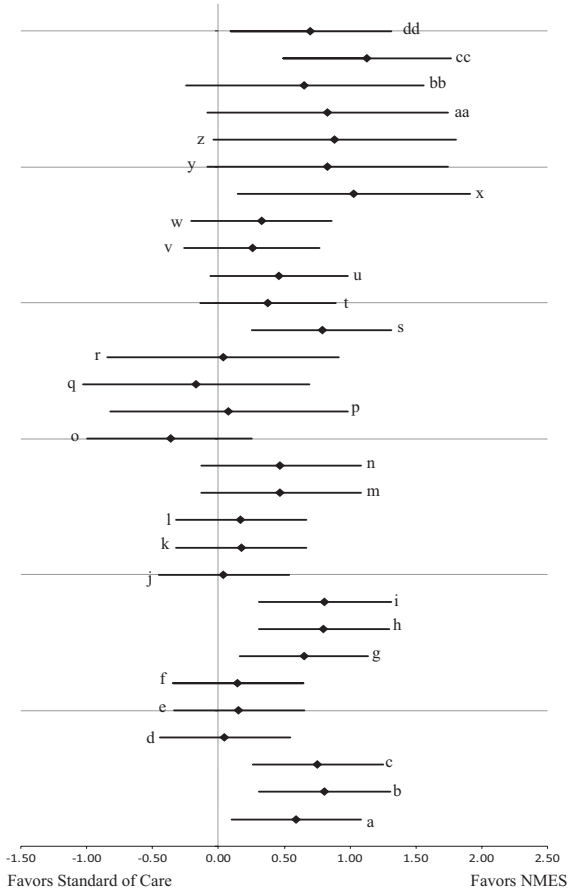
Table 3. Study demographic characteristics for each included article[a]

	NMES, n	Age,[b] y	Control, n	Age, y	Procedure	Strength Measurement
Feil et al[16]						
G1	42[c]	31.1 ± 1.52	44	31.6 ± 1.36	ACL	Isokinetic 90 deg/s, 180 deg/s (N·m/kg)
G2	45[d]	34.8 ± 1.49				
Fitzgerald et al[17]	21	29.2 ± 10.1	22	31.9 ± 10.9	ACL	Isometric index at 60°
Lieber et al[38]	20	28.0 ± 8.2	20	27.3 + 8.5	ACL	Isometric at 90° (N·m)
Sisk et al[70]	11	23.4 ± 7.5	11	23.9 ± 9.2	ACL	Isometric at average of 75° (N·m/kg)
Stevens-Lapsley[76]	35	66.2 ± 9.1	31	64.8 ± 7.7	TKA	Isometric at 60° (N·m/kg)
Wigerstad-Lossing et al[82]	13	28 (21-45)	10	26 (21-33)	ACL	Isometric at 30° (N·m)
Williams et al[83]	13	32.8 ± 7.9	8	32.9 ± 7.7	Menis-cectomy	Isokinetic 120 deg/s, 180 deg/s, 240 deg/s, 300 deg/s (ft·lb)
Yoshida et al[84]						
G1	22[e]	75.9 ± 4.7	22	72.6 ± 6.2	TKA	Isometric at 90° (kgf/kg)
G2	22[f]	71.6 ± 7.0				

ACL, anterior cruciate ligament reconstruction; NMES, neuromuscular electrical stimulation; TKA, total knee arthroplasty.
[a]All comparisons were between NMES and control groups receiving standard of care, except Feil et al[16] and Yoshida et al,[84] which had multiple treatment groups compared with a control group.
[b]Age presented as means ± SDs with the exception of Wigerstad-Lossing et al,[82] which reported median and range.
[c]Feil et al[16] group 1 (G1): Kneehab NMES.
[d]Feil et al[16] group 2 (G2): Ploystim NMES.
[e]Yoshida et al[84] group 1 (G1): motor-level NMES.
[f]Yoshida et al[84] group 2 (G2): sensory-level NMES.

This review sought to ascertain the most effective NMES parameters for recovering postoperative quadriceps strength. Evaluation of all the included articles revealed large variations in the parameters selected for the NMES treatments. In the studies with positive effect sizes, some similarities were observed regarding intensity, electrode size, frequency, treatment initiation time, and current of the NMES treatment.[16,76,82,84] Among those studies reporting positive effects, NMES treatment was consistently implemented during the first 2 postoperative weeks[16,76,82,84] at an intensity level of maximum toleration[76,82,84] with a biphasic current using electrodes ≥40 cm^2. Furthermore, Feil et al[16] and Stevens-Lapsley et al[76] both used at least 2 large electrodes (>96 cm^2) at a frequency of 50 Hz and prescribed NMES multiple times per day. Of the remaining parameters, there were several inconsistencies among the 4 studies; thus, a definitive consensus about the effects of each parameter on quadriceps strength was not possible. However, a summary of the similarities among the available parameters was compiled to provide a recommendation of the optimal parameter selections for recovering quadriceps strength after surgery. All these parameters will be discussed in further detail.

Intensity (current amplitude) is emerging as a critical parameter for regaining quadriceps strength.[28,77] The studies with large treatment effects[76,82,84] identified in this review prescribed intensity at a level of maximal tolerance with an emphasis on progressive intensity escalation.[76,82,84] Specifically, Yoshida et al,[84] who had the largest treatment effect, required the participants to maintain an intensity level that produced a visible muscle contraction during the entire treatment for inclusion in the study. These observations are consistent with other literature reporting a linear relationship between the level of intensity during an NMES treatment and the quadriceps strength.[43,73,77] The only study to specifically report that intensity level was unadjusted, not increased within or across treatment sessions, and did not find a statistical difference between groups.[38] Therefore, to maximize motor unit recruitment and



	Article	ES	Lower	Upper
a	Feil et al 6wk (Group 1) 90°/s[16]	0.59	0.10	1.08
b	Feil et al 12wk (Group1) 90°/s[16]	0.81	0.31	1.31
c	Feil et al 24wk (Group1) 90°/s[16]	0.76	0.26	1.25
d	Feil et al 6wk (Group 2) 90°/s[16]	0.14	-0.35	0.64
e	Feil et al 12wk (Group2) 90°/s[16]	0.28	-0.22	0.78
f	Feil et al 24wk (Group2) 90°/s[16]	0.29	-0.21	0.79
g	Feil et al 6wk (Group 1) 180°/s[16]	0.65	0.16	1.14
h	Feil et al 12wk (Group1) 180°/s[16]	0.80	0.31	1.30
i	Feil et al 24wk (Group1) 180°/s[16]	0.81	0.31	1.31
j	Feil et al 6wk (Group 2) 180°/s[16]	0.04	-0.45	0.54
k	Feil et al 12wk (Group2) 180°/s[16]	0.18	-0.32	0.67
l	Feil et al 24wk (Group2) 180°/s[16]	0.17	-0.32	0.67
m	Fitzgerald et al 12wk[17]	0.47	-0.13	1.08
n	Fitzgerald et al 16wk[17]	0.47	-0.13	1.08
o	Lieber et al[38]	-0.37	-1.00	0.25
p	Sisk et al 7wks[70]	0.08	-0.82	0.98
q	Sisk et al 8wks[70]	-0.17	-1.03	0.69
r	Sisk et al 9wks[70]	0.04	-0.84	0.92
s	Stevens-Lapsley et al 3.5wks[76]	0.79	0.25	1.31
t	Stevens-Lapsley et al 6.5wks[76]	0.38	-0.14	0.89
u	Stevens-Lapsley et al 13wks[76]	0.46	-0.06	0.98
v	Stevens-Lapsley et al 26wks[76]	0.26	-0.26	0.77
w	Stevens-Lapsley et al 52wks[76]	0.33	-0.21	0.86
x	Wigerstad-Lossing et al[82]	1.03	0.15	1.91
y	Williams et al 120°/s[83]	0.83	-0.09	1.74
z	Williams et al 180°/s[83]	0.89	-0.04	1.81
aa	Williams et al 240°/s[83]	0.83	-0.09	1.75
bb	Williams et al 300°/s[83]	0.65	-0.25	1.56
cc	Yoshida (G1) 4wks[84]	1.13	0.49	1.77
dd	Yoshida (G2) 4wks[84]	0.70	0.09	1.31

Figure 2. Hedge *g* effect sizes and 95% CIs for the effect of the neuromuscular electrical stimulation (NMES) treatment on postoperative quadriceps strength. Every time point at which postoperative quadriceps strength was measured is presented. All comparisons were between NMES and control groups. Feil et al[16] G1, group 1 (Kneehab); G2, group 2 (Polystim) and Yoshida e al[84] G1, motor-level NMES; G2, sensory-level NMES.

achieve a forceful, sustained muscle contraction, a high intensity level should be applied and progressively increased throughout treatment.

Undoubtedly, intensity is one of the more difficult parameters to control due to the limiting factor of patients' perceived comfort.[66] Patients also generally have control of this parameter during an NMES treatment; thus, if the patient experiences too much discomfort during the treatment, the patient may refrain from increasing the intensity or even decrease the intensity. In addition to educating patients on the anticipated treatment discomfort and the effects of accommodation and habituation,[40,52,64] one strategy to address patient discomfort is the use of large electrodes to decrease current density.[2,31,66] All studies demonstrating a large posttreatment effect utilized electrodes ≥40 cm^2 in size.[16,76,82,84] It is recommended to use large electrodes and to routinely encourage the patient to increase the intensity both within and between treatment sessions in order to maximize the current intensity a patient can tolerate during NMES.

Another parameter of consensus for those studies showing a large treatment effect was the use of a frequency high enough to achieve a sustained tetanic contraction. Three of the studies[16,76,84] with a positive treatment effect implemented a frequency ≥50 Hz while the other study[82] utilized a frequency of 30 Hz. Examining the recommendations within the literature for recovering muscle strength, clinicians have been advised to utilize a frequency around 50 Hz in order to minimize excessive fatigue.[41,66] Furthermore, the contraction produced by the higher frequencies (50 and 100 Hz) is reported to be smoother,[66] more comfortable,[29] and resulting in increased muscular force production.[14] All the frequencies reported in this review are supported based on the property of summation, where a frequency >30 Hz is necessary to sustain a tetanic contraction.[66]

All the NMES treatments within the studies with large treatment effects were implemented within the first 2 postoperative weeks.[16,76,82,84] It is theorized that the early positive effect of NMES on regaining quadriceps strength is

Table 4. Neuromuscular electrical stimulation (NMES) treatment administration and setup parameters utilized in the included articles[a]

	Treatment Volume	Total Active Treatment Time, min	NMES	Time Initiated Postoperatively	Muscle Contraction	Knee Angle
Feil et al[16]						
G1[b]	12 wk (20 min 3×/d, 5 d/wk)	1200	NMES (battery)	3rd to 4th day	Active	Full extension
G2[c]	12 wk (20 min 3×/d, 5 d/wk)	1200	Polystim (battery)	3rd to 4th day	Active	Full extension
Fitzgerald et al[17]	11 wk (11-12 min/d, 2 d/wk)	40 min 19 s to 44 min	NMES (AC power)	Average 12 d	Passive	Full extension
Lieber et al[38]	4 wk (30 min/d, 5 d/wk)	200	NMES (AC power)	2-6 wk	—	—
Sisk et al[70]	6 wk (8 h/d, 7 d/wk)	5040	NMES (battery)	2nd day	Active or passive	Week 1-4: 45°-50° of flexion Week 5-6: 45°-90° of flexion
Stevens-Lapsley et al[76]	6 wk (15 min 2×/d, 7 d/wk)	157 min 30 s	NMES (battery)	2nd day	Passive	60° of flexion
Wigerstad-Lossing et al[82]	6 wk (40 min/d, 3d /wk)	270	NMES (battery)	2nd day	Active	20°-30° of flexion
Williams et al[83]	3 wk (10 min/d, 5 d/wk)	34 min 36 s	NMES (AC power)	Average 31 d	—	65° of flexion
Yoshida et al[84]						
G1[d]	2 wk (30 min/d, 5 d/wk)	100	NMES (unknown)	2 wk	Passive	—
G2[e]	2 wk (45 min/d, 5 d/wk)	2700	NMES (unknown)	2 wk	Passive	—

[a]"—" indicates information not provided.
[b]Feil et al[16]: group 1 (G1): Kneehab NMES.
[c]Feil et al[16]: group 2 (G2): Polystim NMES.
[d]Yoshida et al[84]: group 1 (G1): motor-level NMES.
[e]Yoshida et al[84]: group 2 (G2): sensory-level NMES.

Table 5. Neuromuscular electrical stimulation (NMES) treatment parameters utilized in each included article[a]

	Frequency	Duty Cycle, s (on/off)	Ramp Time	Intensity	Pulse Duration	Waveform/ Current	Electrode Size
Feil et al[16]							
G1[b]	50	5/10	2 s/1 s down	—	300-400 μs	—	G1[b]: 10 × 20 cm, 3 × 18 cm, 10 × 7.5 cm, 7 × 14 cm
G2[c]	50	10/20	1.5 s/1 s down	—	—	—	G2[c]: 4 × 70 mm round
Fitzgerald et al[17]	75	10/50	2 s up	MT	N/A	2.5 kHz triangular alternating burst	6.98 × 12.7 cm
Lieber et al[38]	50	10/20	2 s up	MT unadjusted[d]	250 μs	Asymmetrical balanced	—
Sisk et al[70]	40	10/30	0.5 s up	MT	300 μs	Rectangular waveform	5 × 10 cm
Stevens-Lapsley et al[76]	50	15/45	3 s up	MT	250 μs	Symmetrical biphasic	7.6 × 12.7 cm
Wigerstad-Lossing et al[82]	30	6/10	2 s up	MT (65-100 mA)	300 μs	Rectangular asymmetrical balanced biphasic	4 × 10 cm
Williams et al[83]	50	15/50	3.5 s up	MT	N/A	2.5 kHz sinusoidal alternating	—
Yoshida et al[84]							
G1[f]	100	10/20	—	MT[e]	1 ms	Symmetrical biphasic	5 × 9 cm
G2[g]	100	Continuous	—	Sensory-level	1 ms	Symmetrical biphasic	5 × 9 cm

MT, maximal tolerance; N/A, not applicable.
[a]"—" indicates information not provided.
[b]Feil et al[16]: group 1 (G1): Kneehab NMES.
[c]Feil et al[16]: group 2 (G2): Polystim NMES.
[d]Required to produce visible muscle contraction.
[e]Intensity level was set to maximum toleration during the first treatment setup. This level was then utilized throughout the treatment sessions.
[f]Yoshida et al[84]: group 1 (G1): motor-level NMES.
[g]Yoshida et al[84]: group 2 (G2): sensory-level NMES.

attributed to characteristics immediately after surgery, such as muscle activation failure and neuroplastic changes at the cortical level, that impair the ability to generate a muscle contraction after surgery.[62,80] The external stimulation generated by an NMES treatment is believed to assist the muscle in achieving a full contraction when activation failure is present.[55,80] Thus, it is recommended to implement the NMES treatment as early as feasible during the first 2 postoperative weeks.

Current type and waveform shape are also likely to influence NMES effectiveness. The results in this study support the use of a biphasic current. Three[76,82,84] of the 4 studies with positive treatment effects utilized a biphasic current, while the remaining

study with positive effect sizes[16] did not report the type of current generated by the investigated devices. Previous research regarding current has been inconclusive, with both a biphasic current and an alternating current (typically "Russian" current) being supported for quadriceps recovery.[8,32] Less information is available for the waveform shape. Only 1 study with a positive treatment effect reported the waveform shape, rectangular.[82] While there is minimal research documenting the effect of waveform shape on regaining quadriceps strength, the shape of the waveform does appear to have an impact on an individual patient's comfort level.[10] Furthermore, the preferred waveform varies between indviduals.[10] Applying a biphasic current with a waveform shape individualized to the patient's perceived comfort is recommended for an NMES treatment.

In our review, the treatment protocols with positive effects implemented longer pulse durations (250 μs, 300 μs, 400 μs, and 1 ms).[16,17,38,70,76,82,83] A long pulse duration is favored to achieve a greater quadriceps torque.[19,21] A torque-duration curve across pulse durations of 100 to 600 illustrates the curvilinear nature between both variables, with torque increasing with the rise in the pulse duration.[21] It has been reported that a larger area of the muscle is stimulated when using a longer pulse duration (450 μs) compared with a short pulse duration (150 μs).[20] This review supports the use of long pulse durations.

All studies with a large positive effect implemented a duty cycle ratio of 1:2[16,82,84] or 1:3[76] with a ramp time of 2 to 3 seconds. It has been reported that the shorter the rest (off) time applied, the greater the level of muscle fatigue experienced[23,53]; although little information is available on the effect of specific duty cycle times on regaining strength. The ramp time does not appear to have an effect on strength values but rather patient comfort. Increasing ramp time results in a gradual increase in stimulus rather than abruptly administering a strong stimulus.[66] Based on patient endurance and comfort, clinicians may consider a duty cycle between 1:2 and 1:3 with a ramp time of 2 to 3 seconds.

Knee flexion angles ranged from 0° to 60° in the studies with positive effects. An angle of 60° has been shown to produce the largest voluntary knee extension torque during an exercise.[9] However, not all patients can achieve a flexed position immediately after surgery and require position modifications. Thus, clinicians may wish to consider a patient position close to 60° of knee flexion but can consider full knee extension if medically necessary.

Lastly, less information is known about the remaining parameters. Unfortunately, there was insufficient evidence to reach a consensus regarding NMES treatment volume and the long-term effect of the NMES treatment. Treatment sessions ranged from 15 to 40 minutes per session 1 to 3 times per day for 2 to 12 weeks in the studies reviewed with positive effects.[16,17,70,76] Similarly, there was no consensus if adding a voluntary contraction with the stimulus was advantageous. The studies with positive treatment effects were split with 2 studies[16,82] of the 4 studies[16,76,82,84] implementing active contractions during the treatment. Based on neuroplasticity principles, the act of performing a volitional contraction during NMES stimulation may be beneficial for the quadriceps muscle. Introducing a new activity and placing attention on the given task, such as contracting the quadriceps, can increase the motor maps within the cortex.[24,25] The development of this additional motor pattern may assist the participant after the stimulation treatment is discontinued. While these theories are promising, similar to the treatment volume parameter, the results of this review are inconclusive on the inclusion of a voluntary muscular contraction in an NMES treatment.

There are a few potential explanations for the dissimilarities between the reviewed articles or patient groups with small effect sizes and those with larger effect sizes. To start, the intensity level was either only at a sensory level for a group,[84] not reported for a group,[16] or never adjusted during the treatment session.[38] In addition to not changing the intensity level, the control group in Lieber et al[38] was exercised at torque levels that progressively increased to match what would be elicited in the stimulation group, potentially diluting differences between groups. The patients in Sisk et al[70] were instructed to set the intensity during treatment to a level that produced a palpable contraction, but at a maximum comfortable intensity level for 8 hours a day, 7 days a week. Given the extensive treatment duration and that the patients controlled the intensity, it is unknown for how much time the patients utilized a maximum strong intensity level. Both Williams et al[83] and Fitzgerald et al[17] had a smaller total time actively in contraction, ranging from 34 to 40 minutes total, compared with the other studies with positive effects that were over 150 minutes total. Additionally, Williams et al[83] and Lieber et al[38] had a late average start time, respectively, averaging 31 days postoperatively and between 2 and 6 weeks postoperatively. Last, the treatment effect was large initially for Steven-Lapsley et al[76] but gradually diminished over time, which may be explained by the change in the rehabilitation setting. The treatment was initiated and continued inpatient for the first 3 postoperative days before transitioning into the home setting where the patients conducted the treatment for the remaining duration of the treatment program. Furthermore, once transitioned to the home setting, if there was concern about a patient's utilization of the treatment, a research physical therapist visited the patient during the first week postdischarge. The variations in intensity level, time actively in contraction, treatment initiation time, and treatment setting implemented in the studies outlined in this paragraph may have contributed to some of the differences in the reported effectiveness.

Limitations

The number of studies that met inclusion criteria was small, limiting the amount of data available for comparison in the review. Additionally, in some circumstances, parameters were not consistently reported or highly varied between studies. This resulted in a reduction in the number of studies available for synthesis and prohibited a meta-analysis from being performed. Lastly, the majority of the studies reviewed did not monitor treatment adherence or include a compliance diary. Thus, it is

difficult to know if the lack of statistical differences between the groups is due to the parameters selected or adherence to the prescribed treatment.

CONCLUSION

There is SORT level B evidence to support NMES for improving postoperative quadriceps strength. Based on the parameters for which a consensus was observed in those studies demonstrating a large treatment effect, clinicians are encouraged to utilize large electrodes (≥40 cm^2) to deliver a biphasic current with the waveform individualized to the patient's comfort level or an alternating current. The recommended setup parameters are a frequency of 50 Hz or greater with a long pulse duration (250 μs to 1 ms) accompanied by a duty cycle ratio between 1:2 and 1:3 that includes a ramp time of 2 to 3 seconds for patient comfort. The intensity of the stimulation treatment ought to be set at the patient's maximal tolerance level and continually increased. Last, the patient's position can range from full extension to 60° of flexion; however, it is advised to position the patients as close to 60° of flexion as medically safe.

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