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Immediate changes in lumbar multifidus thickness during faradic and interferential current stimulation in recurrent low back pain: a randomized crossover pilot study

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Abstract

Introduction. Neuromuscular electrical stimulation has been widely used to stimulate muscles. Although faradic current (FRD) is commonly used, it may not be suitable for lumbar multifidus activation. Interferential current (IFC) may reduce skin impedance and improve current delivery to the lumbar multifidus muscle. The aim of this study was to explore the lumbar multifidus response to different electrical currents.

Methods. Five participants (age = 24.0, *SD* = 3.9) with recurrent low back pain (rLBP) and at least two episodes in the past 3 months that interfered with activities of daily living or required treatment, and five age, sex, and BMI-matched healthy controls (HC; age = 23.0, *SD* = 2.5) were recruited. FRD and IFC were each applied once per side using a continuous incremental protocol from levels of discomfort (LOD 0–10); no repeated series, repetitions, or fixed on/off duty cycle were used. Ultrasound imaging was used to measure the percent change in lumbar multifidus thickness (primary outcome) at rest and across LOD 0–10. Normality and homogeneity of variances were assessed, and no violations were found. A three-way mixed ANOVA was used to examine the interaction between groups and within-groups (currents) and LOD (0–10), with Greenhouse-Geisser corrections. Post-hoc Bonferroni was also performed.

Results. A significant interaction was found ($p = 0.023$; partial $\eta^2 = 0.36$). In the rLBP group, IFC elicited greater LM thickness change than FRD from LOD 3–10 with large effects (Cohen's $d_z = 1.06–2.08$), reaching 22.35(12.18)% *vs.* 7.08(1.83)% at LOD 10. Between-group differences under IFC were significant at LOD 3–8 with large effects (Cohen's $d = 1.72–2.92$), with 20.45(13.00)% in rLBP *vs.* 4.16(2.79)% in HC at LOD 7.

Conclusions. IFC elicited greater immediate lumbar multifidus thickness change than FRD in participants with rLBP. These pilot findings reflect single-session ultrasound-based responses and do not establish clinical or long-term rehabilitation effectiveness.

Key words: electric stimulation therapy, low back pain, paraspinal muscles, ultrasonography

Introduction

Clinicians have widely used neuromuscular electrical stimulation (NMES) to stimulate the muscles in patients with muscle activation deficit [1–7]. NMES is defined as a form of electrotherapy that applies electrical currents over targeted muscles to produce muscle contractions [4]. While faradic current (FRD) was traditionally applied to stimulate denervated muscles, it remains common in clinical practice for the re-activation of innervated muscles. FRD typically consists of low-frequency (20 to 100 Hz) electrical stimulation [1–5]. Although several studies have demonstrated the usefulness of FRD in treating patients with muscle activation deficits, most of the evidence comes from limb muscles [2–5, 7].

Low back pain (LBP) remains a leading cause of disability globally, with a lifetime prevalence reported as high as 84% [8]. While many acute episodes resolve, the recurrence rate is high (approximately 60–80% of individuals experience a recurrence within one year) [9, 10]. The medical and physiotherapy management of LBP has transitioned from passive modalities toward active functional restoration, specifically targeting the lumbar multifidus (LM) [11]. Physiotherapy interventions often focus on motor control exercises to address the muscle atrophy and activation deficits that persist even after pain subsides [12, 13]. However, some patients struggle to voluntarily recruit the LM due to pain inhibition or altered neural drive, necessitating the use of NMES as an adjunct to facilitate early-stage muscle re-education [14].

One current study using FRD on the lumbar multifidus muscle (LM) demonstrated no additional benefit of this current when combining with stabilization exercises [1]. This lack of efficacy may be attributed to the fact that the LM is a deep stabilizer muscle located close to the lumbar spine [15, 16]. Furthermore, high capacitive skin impedance acts as a significant barrier for low-frequency currents. Because the LM is located deep beneath layers of fascia and adipose tissue, the low-frequency nature of FRD often results in energy dissipation at the skin-electrode interface, potentially failing to reach the threshold required for deep motor unit recruitment [11, 17].

Medium-frequency currents including Russian current and interferential current (IFC) can overcome those limitations of FRD [11, 17]. These current frequencies range between 2000 and 10,000 Hz [11, 17]. Based on the reversed relationship between skin impedance and frequency, high frequency from these currents can considerably reduce skin impedance [11, 17]. Accordingly, medium-frequency currents may reduce skin impedance and facilitate current delivery toward deeper target tissues compared with FRD [11, 17]. Russian current is a traditional medium-frequency NMES that is commonly delivered as burst-modulated alternating current [18]. De-

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pending on the modulation parameters, Russian current may also produce asynchronous depolarization and reduce nerve accommodation [18]. However, conventional Russian current protocols often use relatively fixed burst-modulated parameters. Unlike Russian current, the IFC protocol used in the present study was delivered using a quadripolar crossing configuration with an amplitude-modulated beat frequency and scanning function. This scanning function was intended to vary the stimulation field around the electrode intersection area, which may help reduce accommodation during LM stimulation [17, 19]. Therefore, IFC may be appropriate for stimulating the deep LM.

LM dysfunction may reduce the ability of the LM to contribute to spinal stability; however, the mechanisms underlying altered LM function in rLBP are multifactorial [15, 16, 20]. Although previous studies have reported altered LM size or contractile response in people with LBP [15, 16, 20], ultrasound-derived thickness change does not directly quantify motor unit recruitment, neural activation, or voluntary muscle activation [21, 22]. Therefore, the present study focused on the immediate LM thickness response to FRD and IFC as an indirect estimate of electrically evoked LM contractile response.

In summary, NMES has been commonly used to stimulate muscles. Although FRD is one of the most common currents used in clinical practice, this current might not be suitable to stimulate LM. Theoretically, IFC may reduce skin impedance and facilitate current delivery toward the LM region compared with FRD. However, no study has investigated the difference in LM response to NMES (FRD and IFC) between people with rLBP and without a history of low back pain. Therefore, this study aimed to determine the LM responses to different electrical currents (FRD and IFC) in rLBP and healthy control (HC) groups. We hypothesized that IFC would demonstrate greater LM thickness change than that of FRD in both groups. In addition, people without a history of low back pain should have a greater number of active motor units in the LM; therefore, we hypothesized that the HC group would demonstrate greater LM thickness change than that of the rLBP group when using IFC. Findings from this study may help to provide empirical evidence for clinicians to select appropriate NMES frequency to re-activate LM in patients with rLBP.

Subjects and methods

Study design

This pilot study used a randomized crossover, within-subjects experimental design. Both the rLBP and HC groups received two types of NMES (FRD and IFC) delivered in a randomized order to prevent carryover effects. This design allowed participants to serve as their own controls, minimizing the impact of individual anatomical variability on the primary outcome (percentage change in LM muscle thickness) measured by ultrasound imaging across eleven levels of discomfort (LOD 0–10).

Sample size calculation

The sample size calculation was based on the primary statistical model, a three-way mixed ANOVA with one between-subject factor, group (rLBP and HC), and two within-subject factors, current (FRD and IFC) and LOD (0–10). Because no previous study has directly compared the effects of FRD and IFC on LM thickness change, the expected effect size could not be estimated from prior data. Therefore, Cohen's conventional medium effect size for ANOVA was used (Cohen's $f = 0.25$; small = 0.10, medium = 0.25, large = 0.40). Using an alpha level of 0.05 and 80% power, a total sample size of 10 participants (5 per group) was required. Therefore, our current sample of 10 participants was deemed adequate for this study.

Participants

This study used a sample of convenience. Five participants aged between 20 and 40 years with rLBP during remission, and five age, sex, and BMI-matched healthy controls were recruited from the university physical therapy clinic and surrounding communities. This age range was selected to minimize confounding from age-related degenerative changes, such as spondylosis or severe disc degeneration, which may contribute to pain but do not necessarily reflect primary motor control deficits [23]. Research indicates that younger adults with LBP are more likely to exhibit specific lumbar multifidus (LM) activation deficits that are responsive to neuromuscular re-education [14, 20, 24]. Inclusion criteria for the rLBP group were a recurrent pattern of LBP, and at least two episodes that interfered with activities of daily living or required treatment. This criterion increases the likelihood that the pain is due to an underlying impairment in movement control rather than a transient soft-tissue injury [14, 20, 25]. The HC group consisted of individuals with no history of low back pain in the preceding year to ensure the absence of subclinical impairment in movement control. Participants were excluded if they had (1) clinical signs of systemic disease, (2) definitive neurological signs, (3) previous spinal surgery, (4) osteoporosis, or (5) active treatment of another medical illness that would preclude participating in any aspect of the study. These criteria were strictly applied to minimize adverse risks while isolating functional motor control deficits from confounding structural or pathological conditions.

Interventions

NMES (model Sonopuls 492 combination therapy, Enraf-Nonius BV, the Netherlands) was used to deliver electrical current (FRD or IFC) to stimulate the bilateral LM. For FRD application, four hydrogel surface electrodes (5 × 5 cm) were used. While carbon-rubber electrodes with wet sponges are traditionally used with unidirectional currents to minimize skin irritation, modern high-quality self-adhesive electrodes with balanced pH hydrogels were selected for this study to ensure consistent skin-electrode impedance. We used a four-electrode bipolar configuration attached to the bilateral LM with the superior borders at the L3 level and the inferior borders at the L5 level with 2 cm lateral to the midline (Figure 1A). Electrodes were placed bilaterally at the beginning of testing to standardize placement and reduce repositioning time. However, stimulation intensity was increased only on the tested side while LM thickness was measured on that side. The contralateral electrodes remained in place but were not stimulated during that measurement. After completing one side, the same procedure was repeated on the opposite side. This precise positioning ensures the current spans the L3–L5 segments, targeting the primary motor units of the LM as shown in our experimental protocol. Anatomical landmarks were identified by palpating the iliac crests to determine the L4–L5 interspace. The electrodes were oriented vertically, parallel to the spinal column, to ensure the current flow targeted the deep fibres of the multifidus at the level where clinical atrophy and activation deficits are most prevalent. FRD parameters were set to 20 Hz, with a 1 ms pulse duration and a 50 ms

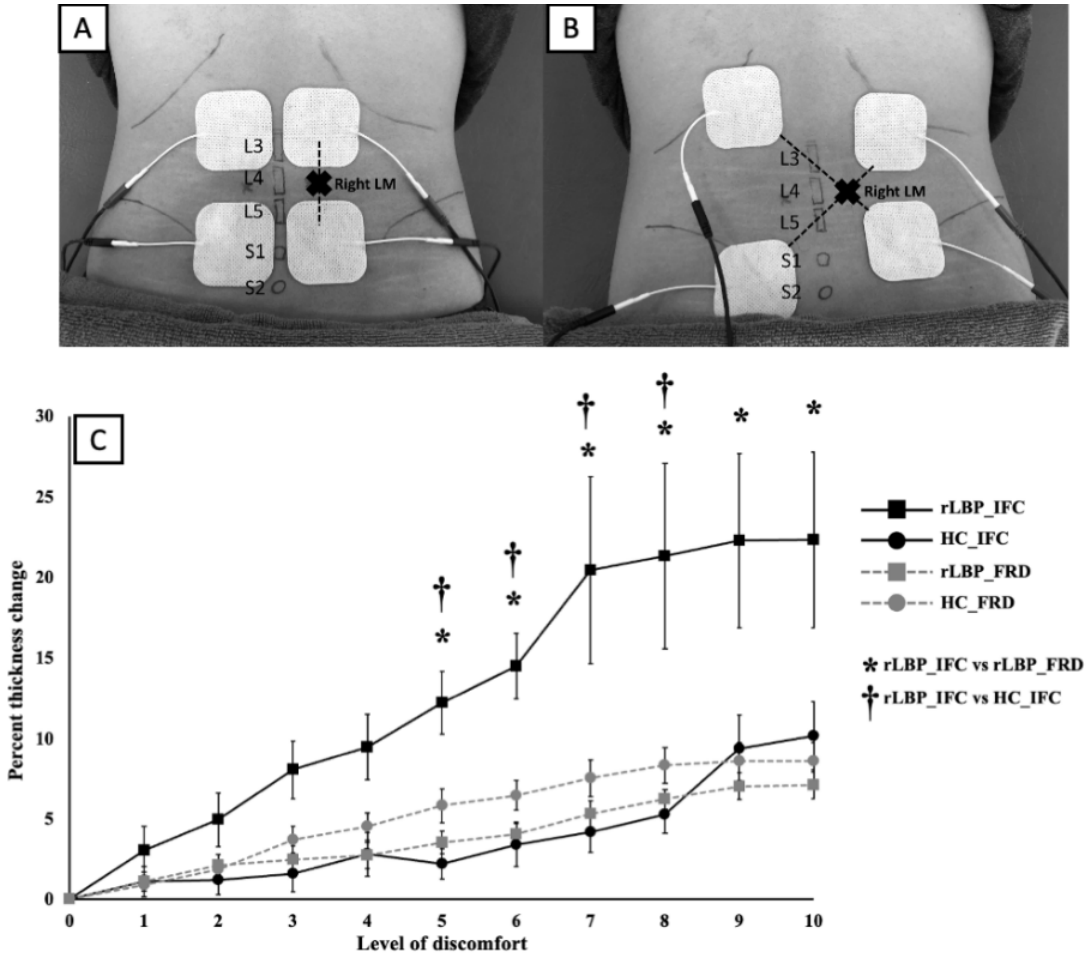


Figure 1. Electrode placements for faradic current (A) and interferential current (B) to stimulate the right lumbar multifidus muscle. Comparisons of the percent lumbar multifidus thickness change (C) between interference current (IFC) and faradic (FRD) in individuals with recurrent low back pain (rLBP) and age, sex, and BMI-matched healthy controls (HC)

pause (Table 1). These parameters were extrapolated from NMES studies applied to the limb muscles [4]. The stimulation frequency was set at 20 Hz for both current types. The stimulation frequency was set at 20 Hz for both current types. This frequency was selected to promote recruitment of lower-threshold, slow motor neurons or Type S motor units, which typically innervate fatigue-resistant oxidative muscle fibres and contribute to tonic postural control. Therefore, the selected frequency was intended to support a contraction pattern relevant to the stabilizing function of the lumbar multifidus, rather than to directly stimulate oxidative fibres [26]. In individuals with recurrent LBP, there is often selective atrophy of these type I fibres and a pathological fibre-type shift towards type II (fast-twitch) glycolytic fibres, which are more fatigable [27]. By utilizing a 20 Hz frequency, the stimulation mimics the natural firing rate of slow-motor units, promoting the endurance and tonic activity necessary for postural control without inducing rapid muscle fatigue often associated with higher frequencies (> 50 Hz) [4]. The intensity was increased in 1 mA increments on the right side, and the right LM thickness was measured for each increment. The participants were asked to rate the level of discomfort (LOD). LOD was defined as the participant-reported level of discomfort during stimulation, measured on an 11-point numeric scale, where 0 indicated no discomfort, and 10 indicated the maximum tolerable discomfort, consistent with the importance of sensory perception in electrotherapy applications [28]. Stimulation intensity was increased incrementally, and ultrasound images were captured when participants reported each LOD level from 0 to 10. Thus, LOD represented perceived stimulation discomfort, not an ultrasound-derived measure. The intensity at maximum LOD was also recorded. Participants were asked to take a 10-minute rest to prevent muscle fatigue and nerve accommodation [17, 19]. Then, the left LM thickness was measured using the same process.

For the IFC application, a quadripolar (crossing) configuration was employed to ensure the interference pattern intersected within the target muscle. One electrode from Channel 1 was placed 3 cm lateral to the inferior border of the L3 spinous process, while the corresponding electrode from Channel 2 was positioned 3 cm lateral to the superior border of the L5 spinous process. The remaining electrodes from each channel were placed diagonally opposite their counterparts. The quadripolar IFC electrode placement was selected to create two intersecting current paths crossing near the centre of the LM. This configuration was intended to direct the interference field toward the target muscle (Figure 1B). This crossing technique was utilized to concentrate the medium-frequency interference at the depth of the LM while minimizing superficial skin stimulation. These electrode locations were reversed to stimulate the opposite side of the LM. A carrier frequency of 6000 Hz was utilized to produce a beat frequency of 20–50 Hz, similar to FRD (Table 1). This medium-frequency carrier was selected to reduce skin impedance and improve comfort during current delivery toward the LM, which lies deep to the thoracolumbar fascia. Compared to lower carrier frequencies (*e.g.*, 1000 Hz), this frequency has been shown to improve participant comfort, allowing for the delivery of

Table 1. Neuromuscular electrical stimulation parameters

Parameter	FRD	IFC
Current type	monophasic rectangular pulsed	amplitude-modulated sine wave
Frequency category	low-frequency	medium-frequency
Carrier frequency	N/A	6000 Hz
Beat/output frequency	20 Hz	20–50 Hz (adjustable)
Pulse duration	1 ms	N/A
Electrode configuration	bipolar (parallel)	quadripolar (crossing)
Modulation/program	constant	1:1 scanning (sweeping)
Stimulation train	continuous during each LOD increment	continuous during each LOD increment
Train on/off time	N/A	N/A
Intensity	0 mA to maximum tolerance	0 mA to maximum tolerance
Stimulation duration	variable; approximately 5 min	variable; approximately 5 min
Rest between currents	10 min	10 min

FRD – faradic current, IFC – interferential current, LOD – level of discomfort, N/A – not applicable

therapeutic current intensities necessary for deep muscle activation without causing superficial skin irritation or discomfort [11, 17]. Both FRD and IFC were continuously delivered during each intensity increment, while ultrasound images were captured. No conventional stimulation train with predefined ON/OFF duty cycles was used. The stimulation parameters for this study were determined following a review of the literature regarding NMES applications for both superficial and deep musculature [1–5, 8, 9]. We acknowledge that parameter selection in NMES is a subject of ongoing debate and may influence both clinical effects and limitations; therefore, our protocol was designed to balance clinical efficacy with experimental control [29]. The researcher repeated the entire data collection process as FRD. The stimulation duration was not fixed because intensity was increased incrementally according to each participant's tolerance across LOD 0–10. The total data collection time for each current was approximately 5 min. A 10-minute rest period was provided between currents to minimize muscle fatigue, nerve accommodation, and carryover effects. Researchers monitored the participants throughout the study. They were asked to report any adverse effects, including muscle fatigue, pain, and other discomfort, during the testing protocol.

Outcome assessments

A B-mode ultrasound imaging device (USI) with a broadband linear array (L12–3) transducer (CX50, Philips, NV, USA) was used to measure bilateral lumbar multifidus muscle (LM) thickness at the L4–5 facet joint. Several studies have demonstrated the validity and reliability of USI to measure the LM thickness among both healthy individuals and patients with LBP [20–22]. Our preliminary work demonstrates excellent within-session intra-rater reliability ($ICC_{3,1}$ = 0.91 and 0.99), and inter-rater reliability ($ICC_{2,2}$ = 0.95) for LM thickness measurement. Test-retest reliability of percent LM thickness change during maximum voluntary isometric contraction was excellent ($ICC_{3,1}$ = 0.98), while 95% confidence minimal detectable change (*MDC*) was 4.39%. The LM thickness data were used to determine the difference in the LM response between HC and rLBP groups.

Participants were assigned a current application order using a computer-generated randomization sequence concealed in sequentially numbered, opaque, sealed envelopes, which were opened only after baseline measurements. The primary researcher handled enrolment, while another researcher assigned the sequence to ensure that the outcome assessor remained blinded to both the participant group and the current type during ultrasound imaging and data analysis.

This study was conducted at the university laboratory. After screening for eligibility and obtaining informed consent, participants were positioned prone with a pillow placed under the abdomen to flatten the lumbar spine. The researcher, who was a physical therapist with 5 years of experience in the musculoskeletal system and physical therapy modalities, identified bilateral L4-5 facet joints (2 cm lateral to the lower half of the L4 spinous process). These locations were used to place the ultrasound transducer to measure LM thickness [20]. Then, the skin at the L4–L5 level was prepared with alcohol to reduce impedance. The experimental session followed a standardized protocol: (1) baseline resting LM thickness was measured using ultrasound, (2) participants were randomized to receive either FRD or IFC first, (3) the intensity of the first current was increased incrementally to identify eleven levels of discomfort (LOD 0 to 10), and 4) ultrasound images were captured at each LOD (Figure 2).

Following the first current, a 10-minute rest period was provided to allow the muscle to return to baseline physiological conditions. The second current was then applied following the same incremental LOD protocol. To ensure data

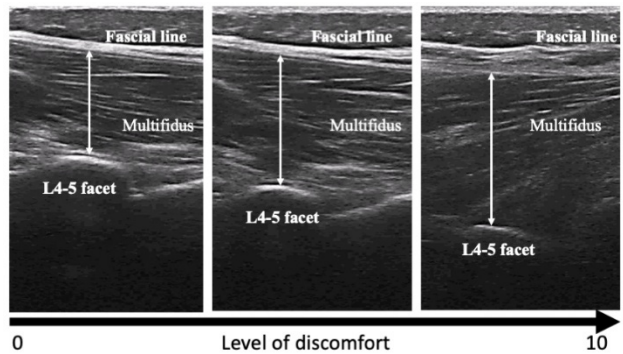


Figure 2. Example of the lumbar multifidus thickness change from level of discomfort 0–10 during the interferential current stimulation

quality and minimize bias, the ultrasound examiner was blinded to the current type being delivered by the stimulator. All measurements were taken by the same experienced examiner to maintain high intra-rater reliability, with three images captured and averaged for each data point to minimize measurement error.

All USI images were transferred to MATLAB (Version R2014a; MathWorks Inc., MA, USA) for data analysis. All images were renamed by the data manager to blind the assessor from the type of electrical current (FRD and IFC). The percent thickness change from resting LM for each LOD was derived. We found no significant difference ($p > 0.05$) between painful and nonpainful sides in participants with rLBP, and between left and right sides in healthy participants. Therefore, we used mean values to compare between groups (HC and rLBP) and currents (FRD and IFC)

Statistical analysis

Statistical analyses were performed using SPSS Program, Version 21 (IBM Corp., NY, USA). Normality was assessed using the Shapiro–Wilk test, and homogeneity of variances was assessed using Levene's test. No violations were found. An independent *t*-test was used to determine any differences in demographic data, as well as resting LM thickness and maximum intensity for each current, while the chi-square test was performed to compare sex between groups. The dependent *t*-test was used to determine the within-group difference in resting LM thickness and maximum intensity between the two currents. This analysis was performed to ensure baseline stability between interventions; specifically, resting LM thickness was compared before applying each current to verify that the randomized order and 10-minute rest period prevented carryover effects. The dependent *t*-test was also used to compare the maximum tolerated intensity between FRD and IFC within each group. This enabled the determination of whether the medium-frequency IFC allowed significantly greater intensity titration than the monophasic FRD. A three-way mixed ANOVA was used to determine the interaction effect of between-group (HC and rLBP) and within-group current (FRD and IFC) and LOD (0 to 10). Greenhouse-Geisser correction was used when the assumption of sphericity was violated. Post-hoc multiple comparisons with Bonferroni were also performed. The significance level was set at 0.05 for all analyses. Given the pilot sample size, the three-way mixed ANOVA and Bonferroni post-hoc comparisons were interpreted cautiously. The interaction effects and post-hoc findings should be considered exploratory and hypothesis-generating. To reduce overreliance on *p*-values, findings were interpreted alongside effect sizes and the 95% confidence interval for the minimal detectable change (*MDC* = 4.39%).

Results

Demographic data are presented in Table 2. Statistical analysis demonstrated no significant difference ($p > 0.05$) in age, sex, BMI, resting LM thickness, and maximum intensity in both FRD and IFC between HC and rLBP groups. In addition, within-group LM thickness demonstrated no significant difference ($p > 0.05$) between FRD and IFC. However, within-group comparison in the rLBP group demonstrated a trend ($p = 0.075$) showing greater IFC intensity (mean = 29.3, *SD* = 9.3 mA) than the FRD intensity (mean = 24.6, *SD* = 7.6 mA) counterpart. Exploratory statistical analysis showed a group × current × LOD interaction ($p = 0.023$; partial $\eta^2 = 0.36$). Post-hoc multiple comparisons (Table 3 and Figure 1C) demonstrated significant differences ($p < 0.05$) in percent thickness change under IFC between groups at LOD-3 to LOD-8, while trends were observed at LOD-9 and LOD-10 ($p = 0.057$ and 0.07, respectively). These differences between groups exceeded the MDC (4.39%) and yielded larger effect sizes (Table 3). No significant difference ($p > 0.05$) between groups was found under FRD. When comparing FRD and IFC, significant differences ($p < 0.05$) were found only in the rLBP group at LOD-3 to LOD-10 with large effect sizes, and these differences were beyond MDC as well (Table 3). No adverse events occurred in this study.

Table 2. Participant demographics and resting lumbar multifidus muscle thickness data

Demographic data	HC ($n = 5$) mean (*SD*)	rLBP ($n = 5$) mean (*SD*)	*p*-value
Age (years)	23.0 (2.5)	24.0 (3.9)	0.65
Sex (female/male)	4/1	4/1	1.00
BMI (kg/m^2)	21.81 (1.89)	21.21 (2.18)	0.66
Resting FRD (cm)	2.28 (0.42)	2.54 (0.53)	0.41
Resting IFC (cm)	2.42 (0.43)	2.37 (0.44)	0.87
Faradic maximal intensity (mA)	25.0 (2.5)	24.6 (7.6)	0.96
Interferential maximal intensity (mA)	26.3 (5.5)	29.3 (9.3)	0.62
Onset (months)	N/A	45.2 (43.7)	N/A
Frequency of episode (per year)	N/A	4.4 (4.5)	N/A
Time since last episode (days)	N/A	43.6 (38.2)	N/A
Averaged duration of an episode (days)	N/A	2.8 (1.4)	N/A
Pain intensity during episode (0 – no pain at all, 10 – worst pain that can be imagined)	N/A	4.0 (0.7)	N/A
Disability during episode (0 – not disabled at all, 10 – totally disabled)	N/A	3.0 (1.6)	N/A
Side of pain (right/left)	N/A	3/2	N/A

HC – healthy control, rLBP – recurrent low back pain, BMI – body mass index, FRD – faradic current, IFC – interferential current, N/A – not available

Discussion

Faradic current vs. interferential current

The findings support our hypothesis that IFC would elicit a greater change in LM thickness than FRD in participants with rLBP. To the best of our knowledge, this is the first study to compare LM responses to NMES between different electrical currents. While FRD is widely used to stimulate muscles in various conditions [2, 3, 5], our findings did not support its use to stimulate the LM in healthy individuals or those with muscle activation deficits. Conversely, our data indicate the clinical usefulness of IFC over FRD, which may assist clini-

Table 3. Mean differences in percent lumbar multifidus muscle thickness change and effect sizes between interference current and faradic in individuals with recurrent low back pain and age-, sex-, and BMI-matched healthy controls (HC) at each level of discomfort

LOD	rLBP				CON				IFC		FRD	
	IFC mean (*SD*)	FRD mean (*SD*)	current difference	effect size (Cohen's d_z)	IFC mean (*SD*)	FRD mean (*SD*)	current difference	effect size (Cohen's d_z)	group difference	effect size (Cohen's *d*)	group difference	effect size (Cohen's *d*)
1	3.02 (3.43)	1.08 (1.32)	1.94	0.48	1.11 (2.12)	0.89 (0.45)	0.22	0.10	1.91	0.67	0.20	0.20
2	4.94 (3.72)	2.12 (1.52)	2.82	0.71	1.17 (1.92)	1.86 (0.69)	–0.69	0.47	3.76	1.27	0.26	0.22
3	8.05 (4.00)	2.46 (1.88)	5.59*	1.20	1.57 (2.46)	3.70 (1.88)	–2.13	0.71	6.48*	1.95	–1.25	0.66
4	9.48 (4.55)	2.72 (1.81)	6.76*	1.20	2.80 (3.05)	4.51 (1.87)	–1.71	0.71	6.68*	1.72	–1.80	0.98
5	12.22 (4.36)	3.53 (1.61)	8.69*	1.70	2.20 (2.14)	5.82 (2.35)	–3.63	1.30	10.03*	2.92	–2.30	1.14
6	14.52 (4.55)	4.02 (1.75)	10.50*	2.08	3.38 (2.98)	6.46 (2.04)	–3.09	0.96	11.15*	2.90	–2.44	1.28
7	20.45 (13.00)	5.29 (1.82)	15.16*	1.06	4.16 (2.79)	7.53 (2.57)	–3.36	1.04	16.29*	1.73	–2.23	1.00
8	21.33 (12.87)	6.21 (1.34)	15.13*	1.16	5.27 (2.61)	8.32 (2.51)	–3.05	0.86	16.06*	1.73	–2.12	1.05
9	22.30 (12.11)	7.03 (1.86)	15.27*	1.24	9.37 (4.67)	8.58 (2.66)	0.80	0.15	12.93*	1.41	–1.55	0.67
10	22.35 (12.18)	7.08 (1.83)	15.27*	1.23	10.16 (4.72)	8.58 (2.66)	1.59	0.31	12.19*	1.32	–1.50	0.65

LOD – level of discomfort, rLBP – recurrent low back pain, CON – healthy control, IFC – interferential current, FRD – faradic current
* differences in percent lumbar multifidus muscle thickness change between currents (IFC and FRD) and groups (rLBP and CON) greater than 95% confidence minimal detectable change (*MDC* = 4.39%)

cians in selecting the appropriate NMES frequency to re-activate the LM in patients with rLBP [30, 31]. Although IFC elicited greater immediate LM thickness change in the rLBP group, this should not be interpreted as evidence that medium-frequency currents are superior for NMES training. Previous studies reported comparable torque and discomfort between kHz-frequency alternating current and pulsed current when phase duration was matched, as well as frequency-dependent training adaptations. Therefore, our findings reflect immediate LM contractile response to the selected parameters, not long-term training efficacy [32, 33].

Current penetration, comfort, and carrier frequency

The greater LM thickness change observed with IFC may partly relate to the use of a medium-frequency carrier, which can reduce skin impedance and improve comfort compared with low-frequency stimulation [11, 17, 18]. The difference in comfort between the two currents is largely attributed to pulse duration. The IFC frequency of 6000 Hz was produced with a pulse duration of 0.167 ms (phase duration of 0.083 ms), whereas the pulse duration for FRD was 1 ms. The shorter pulse duration of IFC avoids stimulating nociceptors, thereby creating a more comfortable current delivery [11, 17]. This was evident in our findings, as participants with rLBP tended to tolerate higher intensities when using IFC.

Although the 6000-Hz carrier frequency used in the present study may have improved comfort and reduced skin impedance, this frequency should not be interpreted as optimal for NMES training. Evidence suggests that carrier frequencies around 4000 Hz are generally more comfortable, whereas frequencies around 1000 Hz may produce greater torque and be more relevant for strengthening [18, 34]. The present study was designed to examine the immediate LM thickness response to FRD and IFC rather than to determine the most effective IFC carrier frequency for therapeutic training. Future studies should compare different IFC carrier frequencies and training dosages to identify the most appropriate parameters for LM re-education in individuals with recurrent LBP. In addition, while pulsed low-frequency currents are safe when parameters are correctly titrated, the alternating nature of IFC inherently minimizes the risk of chemical accumulation under the electrodes, potentially offering a broader safety margin during high-intensity applications [4, 11, 17].

Resistance *vs.* impedance

The greater LM thickness change observed with IFC may partly relate to the use of a medium-frequency carrier, which can reduce skin impedance and improve comfort compared with low-frequency stimulation [11, 17, 18, 28, 29]. In the present study, IFC was delivered using a 6000-Hz carrier frequency, whereas FRD was delivered at 20 Hz. Reduced skin impedance may facilitate current delivery toward the LM. Accordingly, the IFC was better able to deliver electrical current to the deep fibres of the LM, resulting in a greater increase in LM thickness. However, this should not be interpreted as direct evidence of deeper tissue penetration. Therefore, the observed difference in LM thickness response may reflect the selected current parameters and electrode configuration rather than a definitive superiority of medium-frequency current.

Neurophysiological effects on alpha motoneurons

FRD delivers low-frequency pulsed current, which may produce relatively time-locked, synchronous depolarization of excitable motor axons [4, 11]. In contrast, the amplitude-modulated and scanning characteristics of the quadripolar IFC protocol may create more variable spatial and temporal stimulation, potentially promoting less synchronized depolarization and reducing accommodation [11, 17, 19]. However, both FRD and IFC remain forms of externally applied NMES. Therefore, their recruitment patterns differ from voluntary contraction, in which motor units are recruited more asynchronously and are modulated by central neural drive [35]. Thus, the observed LM thickness change should merely reflect an electrically evoked contractile response rather than direct evidence of normal voluntary LM activation.

These neurophysiological explanations should be interpreted cautiously. The present study measured ultrasound-derived LM thickness change, which reflects an electrically evoked contractile response but does not directly quantify

motor unit recruitment patterns, neural activation mechanisms, or voluntary LM activation [21, 22, 35]. Therefore, the proposed differences between FRD and IFC should be considered hypothetical mechanisms that require confirmation using direct neurophysiological measures, such as EMG or motor-unit analysis [22, 35].

Furthermore, the unexpected results in the HC group, in which no significant difference in current was found, may be explained by muscle neurophysiology. The LM function in stabilizing the lumbar spine involves length-dependent muscle activation patterns [36] mediated by gamma motor neurons in response to afferent signals from mechanoreceptors (muscle spindles) [36, 37]. In healthy individuals, IFC might induce a contraction that activates intact mechanoreceptors, triggering a reflex inhibition to protect against excessive force output and tissue stress [36, 37]. This potential mechanism likely limited the change in LM thickness under IFC stimulation in the HC group compared with the rLBP group.

Lumbar multifidus muscle thickness

Our findings also demonstrated that IFC intensity should be sufficient to stimulate the LM. According to our study, the LM thickness change between FRD and IFC in the rLBP group, as well as the thickness change between the HC and rLBP groups using IFC, could be first differentiated at the LOD of 3. In clinical practice, several approaches are used to determine NMES intensity. Some studies have used the maximal tolerance level, while others have used the submaximal level [2, 3, 5]. Our findings support the intensity at both levels to stimulate the LM. Additionally, the lack of significant within-group differences in resting LM thickness between FRD and IFC suggests that the randomized order of application did not result in carryover effects.

Study limitations and future research directions

Some limitations encountered in the study should be examined. This study was a part of another preliminary study; therefore, we included a limited number of samples. The small sample size (n=10) limits the reliability and interpretability of the three-way ANOVA model, particularly because multiple LOD levels were included. Therefore, interaction effects and Bonferroni-adjusted post-hoc comparisons should be interpreted cautiously and considered preliminary. Larger adequately powered studies are required to confirm these findings. This cohort was used to establish “proof of concept” rather than definitive population-wide reliability. We used the effect sizes and MDC in conjunction with statistical analysis. We found that the results with significant differences exceeded the MDC (4.39%) and yielded large effect sizes (effect size > 0.80). Therefore, we can confidently interpret our findings as true differences rather than measurement errors. Because participants were recruited using convenience sampling, random sampling was not fully achieved, which may limit generalizability and introduce a selection bias. Although participants aged 20–40 years were eligible, the recruited sample consisted predominantly of young adults in their early 20s; therefore, the findings may not be generalizable to the full eligible age range. Future NMES studies with larger and more diverse samples are needed to validate our findings. Although the IFC electrode placement was designed to direct two intersecting current paths towards the LM, strict electrode equidistance was not maintained. This may have affected the depth and focus of the resultant interference pattern. Furthermore, the IFC beat frequency of 20–50 Hz was selected to provide low-frequency motor-unit depolarization comparable to the 20-Hz FRD protocol while using a medium-frequency carrier to reduce skin impedance. However, the variable beat frequency may have introduced variability in motor neuron recruitment compared with fixed-frequency stimulation. The primary objective of this study was to investigate the response to two different electrical currents among participants with rLBP and healthy individuals. Thus, we did not collect the retention data. This could have limited clinical application, as retention represents important information that helps clinicians determine the most appropriate dose for an intervention. However, findings from our study indicating the clinical usefulness of the IFC over the FRD could help clinicians to select appropriate NMES frequency to re-activate LM in patients with rLBP [38]. Although self-adhesive electrodes were used to ensure consistent placement, monophasic currents may increase concerns related to skin-electrode impedance and pH-related skin irritation. No adverse effects, including skin irritation, were reported in the present study. However, future studies should consider monitoring skin impedance and skin response, especially when using monophasic currents.

Conclusions

The present pilot study showed that IFC elicited greater immediate LM thickness change than FRD in participants with rLBP, whereas this difference was not observed in healthy controls. However, because of the small sample size and single-session design, these findings should be considered preliminary. Larger studies are needed to confirm whether IFC provides meaningful clinical or training benefits for LM re-education in individuals with rLBP.

Data availability statement

The datasets used and/or analyzed during this study would be available from corresponding author upon reasonable request.

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Ethical approval

The research related to human use complied with all the relevant national regulations and institutional policies, followed the tenets of the Declaration of Helsinki, and was approved by the Mahidol University Institutional Review Board (approval No.: COA No. MU-CIRB 2018/215.0712) and registered in ClinicalTrials.gov (ID: NCT03786627).

Informed consent

Informed consent was obtained from all individuals included in this study. All participants provided written informed consent prior to participation.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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