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Original Research

Effect of Neuromuscular Electrical Stimulation Training on Control of Involuntary Muscular Torque and Stimulation Intensity in Older Adults

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ABSTRACT

International Journal of Exercise Science 16(3): 482-496, 2023. The purpose of this study was to examine the effects of a 4-week neuromuscular electrical stimulation (NMES) training regimen on involuntary torque output and electrical stimulation intensity in older adults. Twelve older adults (ages: 68.4 ± 6.5 years; men: n = 6, women: n = 6; weight: 158.6 ± 27.3 lbs; height: 65.2 ± 2.1 in) received submaximal intensity NMES to the quadriceps for 4 weeks to determine training-related changes in stimulation intensity and involuntary control of muscular torque during the NMES protocol. Two-way repeated measures ANOVAs were used to compare torque parameters and stimulation intensity between days and across protocol time bins. After training, stimulation intensity and torque increased over the course of the NMES protocol, while torque decreased during the protocol pre-training. These results suggest that muscular endurance of involuntary muscle contraction is increased with NMES training, and that stimulation intensity should be increased throughout the course of training to augment muscular torque output.

KEY WORDS: Accommodation; evoked contractions; muscular endurance; muscular force; physical rehabilitation, older adults

INTRODUCTION

Neuromuscular electrical stimulation (NMES) training has been used to induce skeletal muscle adaptations, such as increased muscle mass, strength, and endurance (5, 6, 12, 16, 20). When designing an NMES training protocol, stimulation intensity (the electrical current delivered to the muscle to induce involuntary muscle contraction) can be used to control torque output and is an important but often overlooked parameter. Although stimulation intensity can be easily adjusted, it is often poorly controlled experimentally and clinically, as it is often adjusted to patient tolerance (6, 10, 12, 20) or to produce a visible muscle contraction (6, 10, 25). These methods; however, may not provide muscle fibers with the optimal overload required to produce desired motor output, and in turn, augment muscular adaptations.

Increasing the electrical current delivered to the muscle during NMES is critical to prevent accommodation the muscle experiences. Accommodation has previously been defined as "the transient but reversible increased threshold of nerve excitation" (1) and has been observed during acute (17, 19, 25) and repeated bouts of NMES (20). Physiologically, accommodation to the electrical current results in decreased sensitivity of the muscle fibers to a given electrical stimulation intensity, resulting in depolarization of fewer muscle fibers (11, 14), subsequent reduction in cross-bridge cycling, and ultimately, decreased force production (7). Further, reduction in torque output is a consequence of the rapid rate of muscular fatigue experienced during NMES, which is enhanced due to reverse motor unit recruitment order and synchronous activation of motor units during electrically evoked muscle contractions (8, 13, 19). Additionally, strength improvements post-NMES training are positively correlated to the degree of electrically evoked torque produced during the training protocol (20). Therefore, stimulation intensity increases may be needed to overcome accommodation and neuromuscular fatigue to serve as a means to maximize electrically evoked torque output and produce stronger muscle contractions during each NMES training session.

Often, NMES protocols are administered at maximum tolerable stimulation intensity. In young, athletic men it was determined that the maximal tolerable intensity increased during an individual session and over the course of the training regimen (20). Maximal tolerable intensity may be suitable for young athletes accustomed to intense workouts involving heavy loads or high intensities; however, this may not be feasible for older adults and clinical populations due to the discomfort individuals may experience during NMES application. This discomfort is likely to decrease program adherence, especially for those who may already be reluctant to perform exercise. Additionally, maximal tolerable NMES intensity is highly subjective and variable among individuals (20) and standardized and controlled methods of current delivery are methodologically important for comparison of involuntary torque output parameters between participants and training sessions. Further, use of submaximal intensity stimulation allows for the design of the NMES protocol to be more similar to that of a voluntary resistance training program in which training intensity/training load is often defined as percent 1-repetition maximum (% 1-RM). Use of submaximal stimulation intensity allows for the training intensity to be set relative to each participant's strength which can be measured as a percent maximal voluntary contraction (%MVC) for isometric contractions and is comparable to using % 1-RM in a voluntary resistance training program. The goal of a submaximal strengthening program is to provide each participant with the same level of "overload" or overload relative to the participant's individual strength as a means to induce similar adaptations across subjects in response to the training protocol. Additionally, voluntary resistance training is typically performed at submaximal intensities (% 1-RM) over the course of long-term training, which is of particular importance for older adults; accordingly, use of submaximal intensity NMES may be more comparable to traditional, voluntary resistance training programs for older adults. Thus, it is important to understand the stimulation intensity adjustments needed and the resulting involuntary torque output profile produced during administration of NMES protocols that use submaximal stimulation intensity pre-post NMES training.

In previous work using a submaximal intensity stimulation NMES protocol in young healthy adults, the stimulation intensity required to achieve a 15% MVC target torque output increased throughout an acute NMES session, while torque declined (19). This previous work examined stimulation intensity and torque changes during an acute NMES bout; however, the effect of submaximal intensity NMES training (repeated bouts) on involuntary force output and stimulation intensity requirements remains unknown. Therefore, the purpose of this study was to determine the effect of a 4-week submaximal intensity NMES training regimen on control of involuntary torque output and electrical stimulation intensity required to achieve a target torque output in older adults. We hypothesized that following 4 weeks of NMES training in older adults, 1) involuntary motor output during the NMES protocol would be higher compared to pre-training, and 2) higher stimulation intensity requirements would be needed to achieve the submaximal target torque output. The rationale for use of older adult participants is that the findings of this study may have greater implications and be more clinically viable for this population, as older adults may be more hesitant or be unable to perform traditional voluntary resistance training. Thus, older adults may benefit from utilizing NMES training in a clinical or fitness setting as an alternative modality. The findings of this study also have important implications for NMES and functional electrical stimulation (FES) protocol design for research and evidence-based physical rehabilitation protocol design.

METHODS

Participants

A power analysis conducted with SPSS 26 (Version 26.0; IBM SPSS, Inc., Chicago, IL) determined that at least 7 participants were needed for a power of 0.80, with an effect size of 1.36 (using pilot data) and $\alpha = 0.05$. Twelve healthy, older adults (6 men, 6 women; age: 68.4 ± 6.5 years) were recruited from the San Marcos/Austin, Texas area. Interested individuals underwent a health history screening to determine study eligibility. Inclusion criteria consisted of individuals who were 60 years of age or older and generally healthy. Individuals were excluded due to the following conditions: participated in regular resistance training exercise or physical rehabilitation of the lower extremity within two months of the study, contraindicating conditions for electrical stimulation (i.e., swollen, infected or inflamed areas, open wounds, or painful areas on the lower limbs, implanted electronics, pacemakers, or implanted stimulators), knee pain/injury, neuromuscular disease, taking insulin for diabetes, or a history of seizures. All participants provided written informed consent. All study procedures complied with the Declaration of Helsinki and were approved by the Texas State University Institutional Review Board (IRB). This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (22).

In brief, participants were first familiarized with the isokinetic dynamometer and then each participant performed MVCs for knee extension. MVCs were taken at least three days before NMES Training Day 1 and were reassessed on NMES Training Day 7. These values were used to calculate 15% MVC, which was designated as the target torque output for the NMES training protocol. Participants underwent 12 NMES training sessions (3x/week for 4 weeks) of the quadriceps muscles. Torque data were recorded during NMES Training Days 1 and 12 and were saved for later analysis of torque parameters.

Protocol

Maximal Voluntary Contraction (MVCs): Participants were asked to refrain from caffeine and tobacco products on MVC testing days and on Training Days 1 and 12, and to avoid exercise for at least 48 hours before these study visits. For MVC testing, participants were seated on an isokinetic dynamometer (Biodex, Systems-4, Shirley, NY) with 60° knee flexion and 85° hip flexion with limb and joint positions secured by straps. Participants were then familiarized with the equipment and MVC testing protocol by performing submaximal and maximal knee extension contractions. A randomization software program (26) randomized the testing order between legs. Next, to determine maximal knee extensor strength, participants performed three isometric MVCs that were held for 4 seconds each. An MVC duration of 4 seconds was selected as this is consistent with previous MVC testing protocols (18, 19, 23). Participants were instructed to contract as fast and forcefully as possible to generate maximum torque output and verbal encouragement was provided. If torque production continued to increase after the third MVC, additional MVCs were performed until torque production was lower than the previous MVC. MVCs were analyzed for peak torque with the highest torque value considered the participant's MVC, which was used to determine the target torque output for the NMES training protocol. MVCs were taken at least three days before Training Day 1 and were reassessed on Training Day 7.

NMES Intervention Protocol: Twelve (Day 1 - Day 12), NMES training sessions of the quadriceps muscles were completed 3x/week for 4 weeks. For each training session, NMES was applied to each leg for 40 minutes, generating a total of 96 muscle contractions for each leg. A constant current stimulator (Digitimer DS7AH, MEPs-LLC, Fort Lauderdale, FL) delivered the NMES through 4 stimulation electrodes (carbon cloth electrodes, 3x5 inches; Axelgaard, LTD, Fallbrook, CA) placed at the proximal and distal aspects of the vastus medialis and lateralis muscles of the quadriceps. For all NMES training sessions, participants were seated on an isokinetic dynamometer (Biodex, Systems-4, Shirley, NY) in the same manner as the MVC testing. NMES protocol parameters consisted of a stimulation frequency of 60 Hz, on-off cycle of 10 seconds on and 15 seconds off, pulse width of 200 μs, and stimulation intensity adjusted to reach a target torque output of 15% of each participant's MVC. Due to rapid muscular torque decline during NMES, the torque output was measured and stimulation intensity was increased every 5 minutes, as needed, to achieve the 15% MVC target torque. All torque data for MVC and NMES training sessions were collected and recorded at a sampling rate of 100 Hz and a Video Graphics Array transferred data from the isokinetic dynamometer (ADInstruments Inc., Colorado Springs, CO) to the data acquisition system (PowerLab 16/35, ADInstruments Inc., Colorado Springs, CO). A randomization software (26) was used to randomize the order in which right and left legs received the stimulation over the 12 training sessions. The 15% MVC target torque calculations were based on the participant's MVC measured prior to Day 1 for training Days 1-6, and the Day 7 MVC was used for training Days 7-12 to progressively overload the muscle and account for potential improvements in MVC over the course of the training regimen. The goal of this study was to determine adaptations regarding involuntary force output during NMES in response to a short-term NMES training program. Since neuromuscular adaptations account for a majority of the training-related changes observed during the first 4-6 weeks of a training regimen (3, 21), a 4-week training intervention was implemented. Additionally, previous studies have demonstrated that 4 weeks of NMES training resulted in increased voluntary strength and muscular endurance (5, 24), providing additional rationale for the length of the training period used in the present study.

Data Analysis: LabChart 8 software (ADInstruments Inc., Colorado Springs, CO) was used to analyze the muscle torque data obtained during the NMES training sessions and MVCs. Each of the 96 contractions for both legs were individually analyzed to measure the following torque output parameters: mean torque (MT), peak torque (PT), and torque time integral (TTI). Additionally, the total torque time integral sum (STTI) was calculated by summating the TTI values for all 96 contractions of the NMES protocol. All Day 1 torque parameters were normalized to the participant's MVC on Day 1 and are expressed as a percentage of MVC (%MVC) on Day 1, while Day 12 torque parameters were normalized to each participant's Day 7 MVC. The average of both legs was used to analyze each torque parameter and stimulation intensity for each subject. For one participant, torque output from the left leg was considered an outlier (> 2 SD from the mean); therefore, for this subject only data from the right leg were used for analysis. The overall average for all torque parameters was calculated over the 40-minute NMES protocol for each participant. Then, the NMES protocol was divided into 25% time-bins: 25% (contractions 1-24), 50% (contractions 25-48), 75% (contractions 49-72), and 100% (contractions 73-96). For each 25% time-bin, the average was calculated for MT, PT, and TTI to examine changes in torque output throughout the protocol. The first five minutes (first 12 muscle contractions) of the NMES protocol were also analyzed for MT, PT, and TTI to evaluate training-related involuntary torque output changes prior to stimulation intensity adjustments.

Stimulation Intensity: The stimulation intensity required to achieve the 15% MVC target torque was recorded at the start of the NMES protocol and every 5 minutes thereafter. The average stimulation intensity for each 20-minute time-bin of the 40-minute protocol was calculated. The 0-minute time-bin represents the stimulation intensity for the first contraction, the 20-minute time-bin represents the average of the stimulation intensities recorded at minutes 5, 10, 15, and 20, and the 40-minute time-bin represents the average of the stimulation intensities recorded at minutes 25, 30, 35, and 40.

Statistical Analysis

Paired sample *t*-tests were used to determine differences in overall mean stimulation intensity and overall MT, PT, TTI, and STTI between Days (Day 1, Day 12). Two-way repeated-measures analysis of variance (ANOVA) were used to compare MT, PT, and TTI between Days and 25% time-bins (25%, 50%, 75%, 100%), between Days and contraction number (contractions #1 - #12) during the first five minutes of the protocol, and to compare stimulation intensity between Days and time (0, 20, 40 minutes). Bonferroni post hoc tests were used to determine statistical significance for multiple pairwise comparisons. Effect size was calculated using Cohen's *d* (no effect: $d < 0.19$; small: $d = 0.2\text{-}0.49$; medium: $d = 0.5\text{-}0.79$; large: $d > 0.8$). Statistical significance was set at $p \leq 0.05$ and all data are reported as mean ± standard error (SE). Statistical analyses were performed using SPSS 26 (Version 26.0; IBM SPSS, Inc., Chicago, IL).

RESULTS

Stimulation intensity compared across 20-minute time-bins of the NMES protocol revealed a statistically significant main effect for Day, with a higher stimulation intensity on Day 12 than Day 1 ($p = 0.027$; $d = 0.46$, small effect; Fig. 1). The main effect for time-bin shows that stimulation intensity increased significantly during the 40-minute protocol ($p < 0.0001$; Fig. 1) and pairwise comparisons indicate that stimulation intensity increased significantly every 20 minutes ($p < 0.0001$; Fig. 1). The interaction between Day and time-bin was not statistically significant ($p = 0.125$). The stimulation intensity values for each NMES training day (Day 1 – Day 12) are displayed in Table 1.

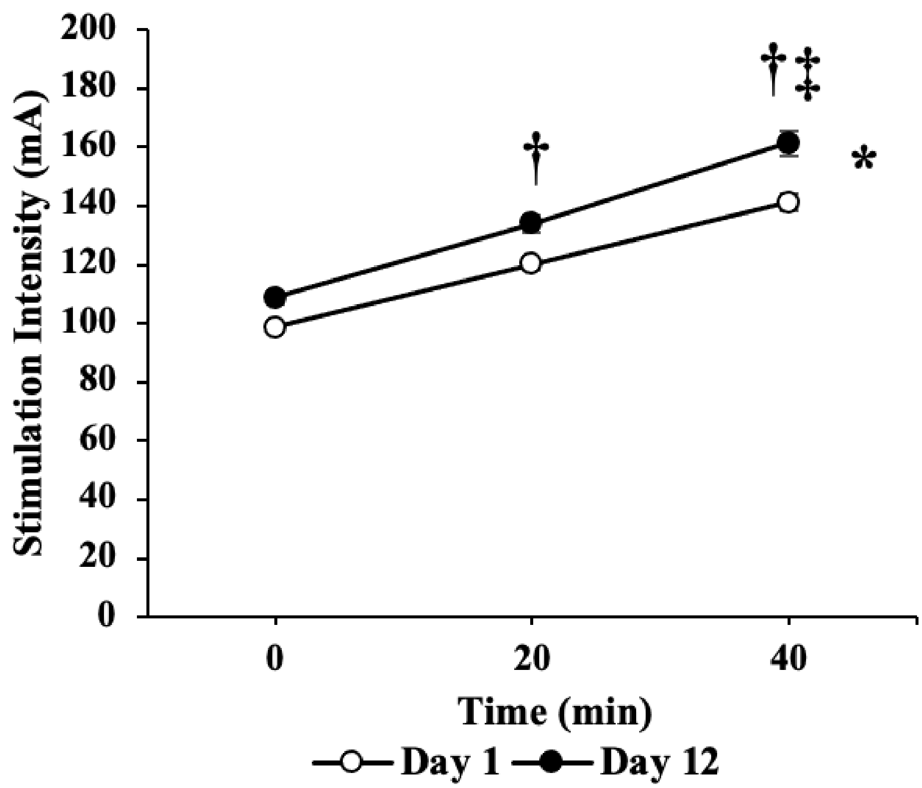

Figure 1. Stimulation intensity over 20-minute time-bins of the 40-minute NMES protocol. * indicates main effect for Day, Day 12 > Day 1 ($p \leq 0.05$). There was a main effect for time-bin ($p < 0.0001$), † indicates a significant increase from the 0-minute time-bin ($p < 0.0001$), ‡ indicates a significant increase from the 20-minute time-bin ($p < 0.0001$).

Table 1. Stimulation intensity over 20-minute-time-bins of the 40-minute NMES protocol for each NMES training day (Day 1 – Day 12). Data are presented as mean ± SE of all subjects.
Stimulation Intensity for each Training Day (mA)

Training Day	0-Minute Time Bin	20-Minute Time Bin	40-Minute Time Bin
1	94.88 ± 0.59	118.79 ± 0.71	147.25 ± 1.03
2	124.94 ± 0.74	147.66 ± 1.05	171.96 ± 1.17
3	122.02 ± 0.85	146.06 ± 1.15	174.95 ± 1.66
4	123.17 ± 0.73	145.36 ± 1.02	172.74 ± 1.46
5	124.19 ± 0.77	148.14 ± 1.12	179.22 ± 1.60
6	126.69 ± 0.87	146.65 ± 1.24	176.70 ± 1.83
7	121.29 ± 0.65	145.09 ± 1.10	183.27 ± 2.28
8	127.96 ± 0.83	151.24 ± 1.21	178.01 ± 1.57
9	122.71 ± 0.79	160.36 ± 3.19	169.65 ± 1.41
10	119.17 ± 0.77	141.39 ± 1.16	169.80 ± 1.76
11	120.50 ± 0.99	147.36 ± 1.33	177.64 ± 1.95
12	108.65 ± 0.66	133.74 ± 1.03	161.41 ± 1.47

mA: milliampere

The overall (for all 96 contractions) MT (p = 0.018; d = 0.62, medium effect), TTI (p = 0.01; d = 0.64, medium effect), and STTI (p = 0.01; d = 0.65, medium effect) were significantly higher on Day 1 than Day 12, and overall PT was not different between Days (p = 0.571; d = 0.16, no effect) (Fig. 2). MT data from one representative participant are displayed for each of the 96 contractions of the 40-minute protocol for both days (Fig. 3).

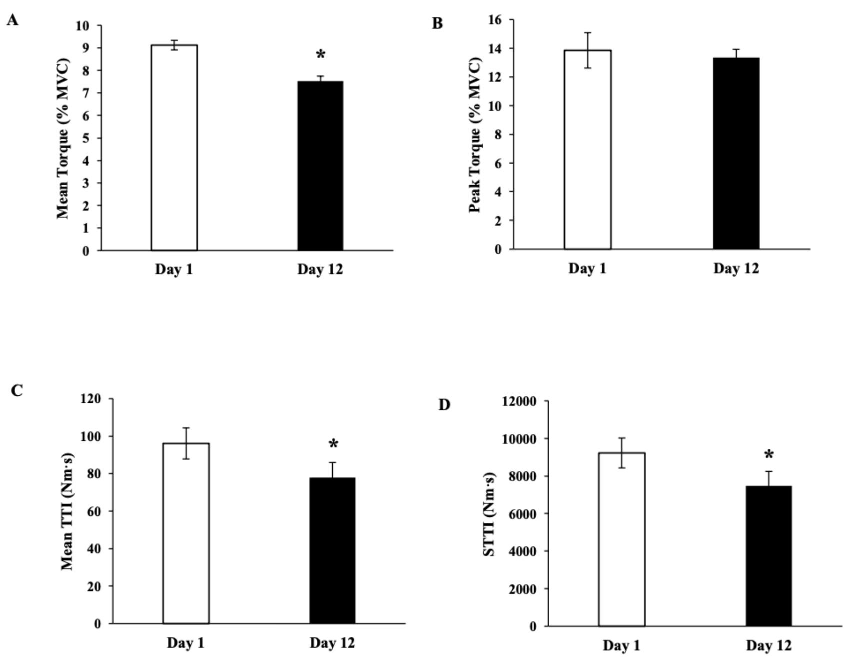

Figure 2. Data represent the overall average for each torque parameter throughout the NMES protocol. * indicates a significant decrease from Day 1 to Day 12. A) Overall MT decreased from Day 1 to Day 12 (p = 0.018). B) Overall PT did not change between days (p > 0.05). C) Overall TTI decreased from Day 1 to Day 12 (p = 0.01). D) STTI decreased from Day 1 to Day 12 (p = 0.01).

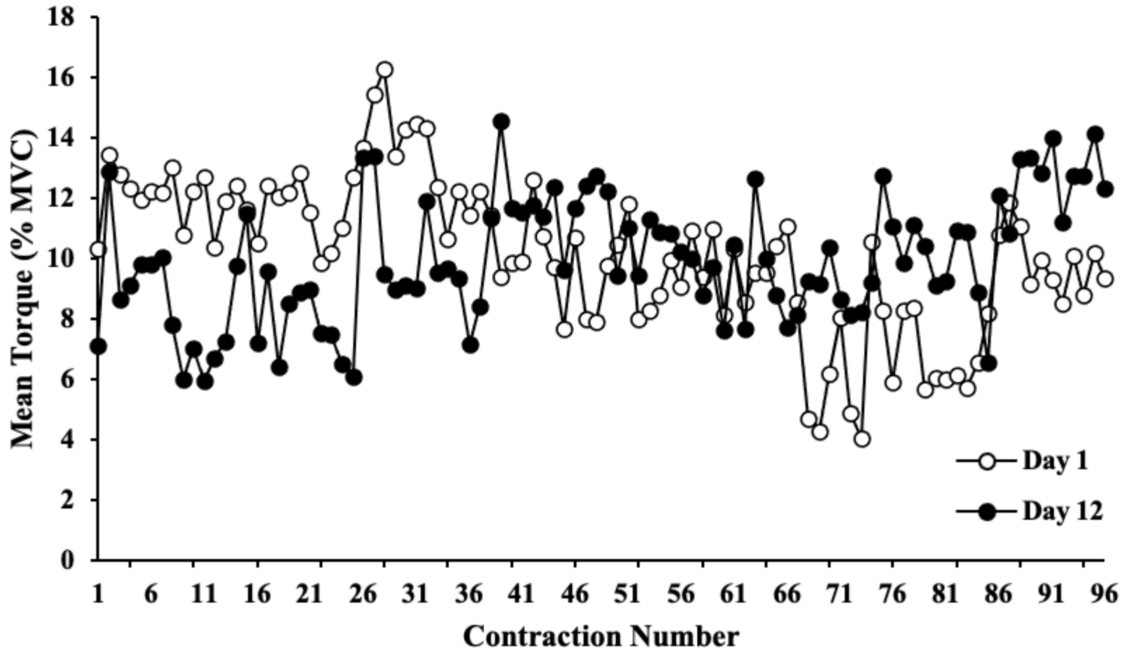

Figure 3. Representative data from one participant during the training sessions on Days 1 and 12 showing MT produced during each contraction of the NMES protocol.

For 25% time-bins, the main effect for Day for MT across time-bins of the protocol was statistically significant, with Day 1 generating greater MT than Day 12 ($p = 0.019$). The main effect for time-bin was not significant ($p = 0.106$); however, there was a significant interaction between Day and time-bin for MT ($p = 0.006$; Fig. 4A). Pairwise comparisons revealed that the 25% bin produced significantly higher MT on Day 1 than Day 12 ($p < 0.0001$; $d = 1.17$, large effect). On Day 1, there were no differences between time-bins ($p > 0.05$); however, on Day 12, the 75% ($p = 0.001$; $d = 0.64$, medium effect) and 100% bins ($p = 0.001$; $d = 0.73$, medium effect) produced significantly greater MT compared to the 25% bin (Fig. 4A). For PT across 25% time-bins, main effects for Day ($p = 0.50$) and time-bin ($p = 0.258$) were not significant. However, the interaction between Day and time-bin was statistically significant ($p = 0.006$) and pairwise comparisons for PT showed the 100% bin was significantly higher on Day 12 than Day 1 ($p = 0.004$; $d = 0.95$, large effect) and on Day 12, the 100% bin was significantly greater than the 25% bin ($p = 0.006$; $d = 1.11$, large effect; Fig. 4B). The main effect for TTI across 25% time-bins of the protocol was statistically significant for Day, with Day 1 generating greater TTI than Day 12 ($p = 0.01$), but the main effect for time-bin was not significant ($p = 0.165$). There was a significant interaction for TTI between Day and time-bin ($p = 0.01$; Fig. 4C) and pairwise comparisons revealed that the 25%-bin was significantly higher on Day 1 than Day 12 ($p < 0.0001$; $d = 1.18$, large effect). On Day 12, the 75% ($p = 0.001$; $d = 0.62$, medium effect) and 100% bins ($p = 0.003$; $d = 0.67$, medium effect) produced significantly greater TTI than the 25% bin. There were no differences across time-bins on Day 1 ($p > 0.05$).

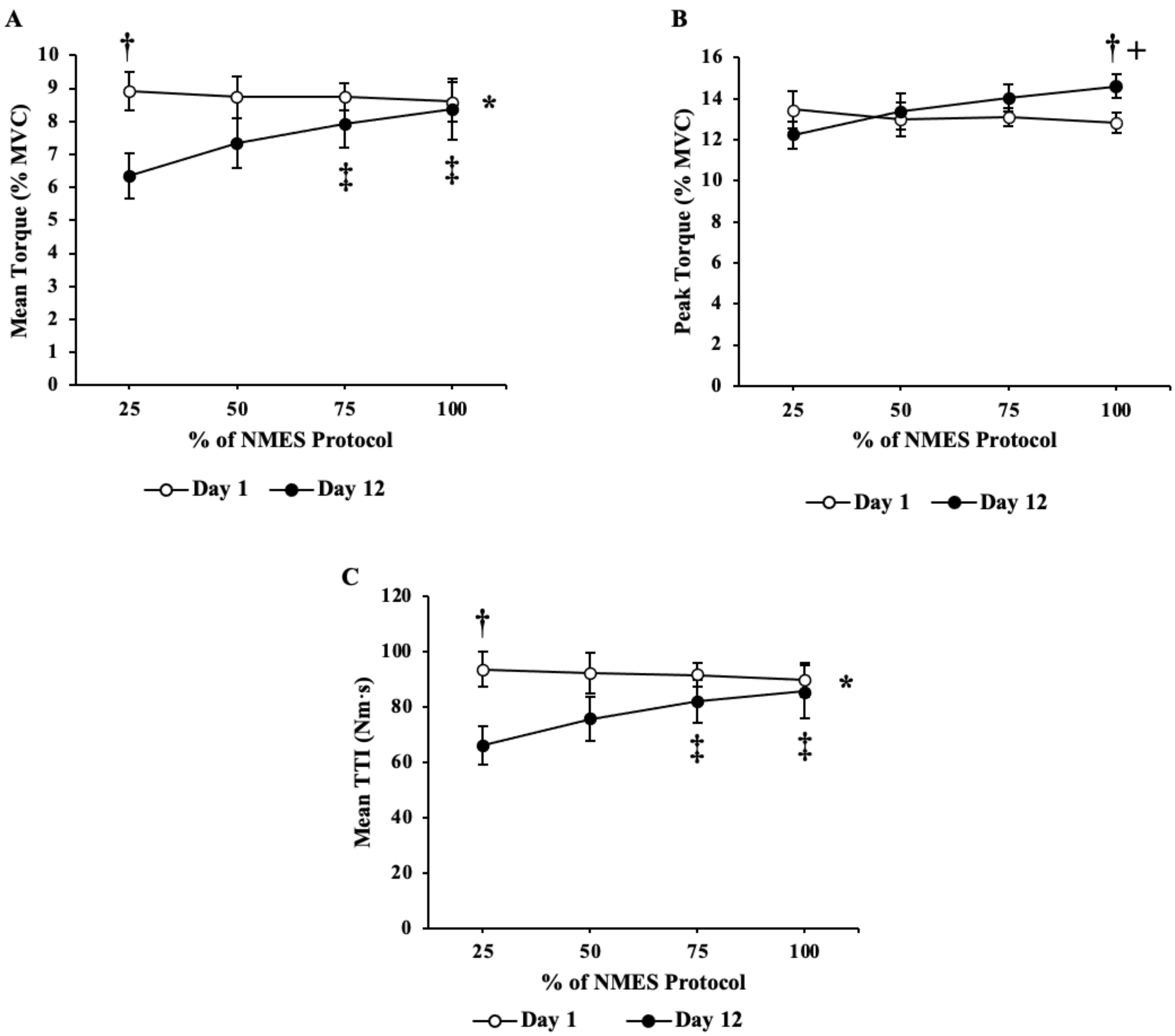

Figure 4. Average values during 25% time-bins over the 40-minute protocol (25%, 50%, 75%, 100% of the NMES protocol time). A) MT, B) PT, C) TTI. * indicates main effect for Day, Day 1 > Day 12 ($p \leq 0.05$). There was a significant interaction effect for Day x time-bin for all three torque parameters ($p < 0.001$); significant pairwise comparisons for MT ($p \leq 0.001$), PT ($p \leq 0.01$), and TTI ($p \leq 0.01$). † indicates 25% time-bin Day 1 > Day 12; ‡ indicates > 25% time-bin on Day 12; **+** indicates 100% time-bin Day 12 > Day 1.

Torque data for the first 5 minutes of the protocol are displayed in Figure 5. MT during the first five minutes showed significant main effects for Day ($p = 0.004$; $d = 0.78$, medium effect), with Day 1 generating greater MT than Day 12, and contraction number across the first 12 contractions of the NMES protocol ($p < 0.0001$). However, there was no significant interaction effect between Day and contraction number for MT ($p = 0.298$). For PT during the first five minutes, the main effect for Day was not significant ($p = 0.313$; $d = 0.29$, small effect), but the main effect for contraction number was significant ($p < 0.0001$). The interaction between Day and contraction number was not significant ($p = 0.316$). For TTI during the first five minutes, the main effect for Day was not significant ($p = 0.071$; $d = 0.93$, large effect), but there was a significant main effect for contraction number ($p < 0.0001$). The interaction between day and contraction number for TTI was not significant ($p = 0.176$).

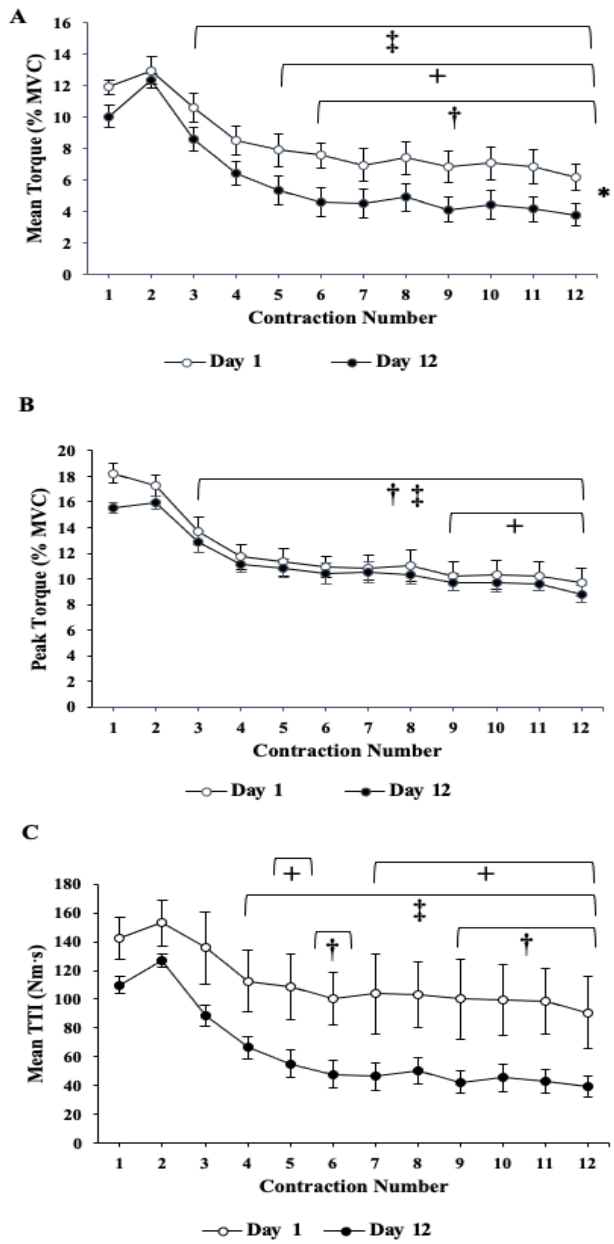

Figure 5. Torque parameters during the first 5 minutes (contractions 1-12) of the NMES protocol with constant stimulation intensity. A) MT, B) PT, C) TTI. * indicates main effect for Day, Day 1 > Day 12 ($p < 0.05$); there was a significant main effect for contraction number for all three torque parameters ($p < 0.0001$) and significant pairwise comparisons are indicated as follows: † < contraction 1, ‡ < contraction 2, **+** < contraction 3, $p < 0.05$ for all indicated comparisons.

DISCUSSION

Previous studies have shown improvements for voluntary muscular strength and voluntary muscular endurance with NMES training (5, 12, 24). To our knowledge, however, this is the first study to report the impact of four weeks of NMES training on 1) control of involuntary torque output produced from the NMES protocol, and 2) the stimulation intensity adjustments needed to achieve a given level of submaximal torque with a submaximal intensity NMES. The primary finding of this study is that during the NMES protocol, torque output significantly increased over the course of the 40-minute protocol on training Day 12, while torque showed a decline during the protocol on Day 1. The ability of the muscle to increase torque production as the protocol progressed on Day 12, but not Day 1, is an important adaptation to highlight and suggests that the 4-week NMES training protocol increased involuntary muscular endurance. Additionally, the stimulation intensity required to achieve the 15% MVC target torque during the NMES protocol was higher on Day 12 compared to Day 1, indicating accommodation to the electrical stimulation, meaning more electrical current was needed to achieve the same muscular torque response following NMES training. Also notable, despite higher stimulation intensity on Day 12, the overall MT and TTI produced during the protocol were lower on Day 12 as compared to Day 1, further suggesting accommodation of the muscle to the electrical stimulation with training.

Following NMES training, significantly higher stimulation intensity was required on training Day 12 than on Day 1 to achieve the submaximal, 15% MVC target torque during the NMES protocol. These data indicate that the muscle is less sensitive to the electrical current after repeated NMES bouts due to accommodation to the electrical current that is used to induce muscle contraction (1). Consequently, higher levels of electrical current are needed with repeated NMES bouts to achieve a given submaximal torque output, which has also been shown with maximum tolerable stimulation intensity with training (20) and during an acute submaximal intensity NMES protocol (18, 19). Furthermore, on both Day 1 and Day 12, during the first 5 minutes of the NMES protocol, MT, PT, and TTI demonstrated declines from the start of the electrical stimulation to the end of the first 5 minutes, before any stimulation intensity increases. These results are similar to previous studies that also reported a decline in peak torque from the first repetition to the tenth (19, 25). Data from the present study further promote the importance of stimulation intensity increases throughout the NMES training to attenuate degradation of torque production by the end of the training session. Often in clinical and research settings, however, the stimulation intensity is set to the patient's tolerance level, is left unchanged or infrequently adjusted (6, 9, 12), or may be set based on visible muscle contraction (6, 25), while few studies have adjusted stimulation intensity level based on a more robust and reproducible criterion (e.g., target torque level) (17–19). Although some protocols have incorporated increases in stimulation intensity over a single NMES session (4, 5, 9, 15, 17–19) or encouraged increases in maximal stimulation (20, 28), to our knowledge, no studies have reported changes in stimulation intensity needed after repeated NMES bouts while using a submaximal stimulation intensity. Unchanged or infrequently adjusted stimulation intensity levels can result in diminished sensations experienced by the patient, which may be preferred due to the absence of discomfort; however, evidence from previous studies and the present data indicate this may not optimize force production or subsequent muscle adaptations geared to improve force production or strength gains (20). Thus, when designing NMES training protocols, systematic stimulation intensity increases should be implemented during individual sessions as well as with repeated long-term training to progressively overload the muscle and generate greater overall torque production which may lead to enhanced muscular performance.

The primary finding in the torque output profile is observed across the 25% time-bins in which torque output increased over the course of the NMES protocol on Day 12, while torque output decreased during the protocol on Day 1. Both the 75% and 100% bins were significantly higher than the 25% bin for MT and TTI on Day 12. The increase in torque during the protocol on Day 12 occurred despite a lower initial torque output and less overall torque production on Day 12 for MT and TTI. In contrast, torque output showed a non-significant decline at the same points of the protocol on Day 1. Consistent with Day 1 data from the present study in which torque declined as the protocol progressed, Randolph et al. (25) also reported a decline in torque and suggested repeated NMES contractions may exhibit accommodation to current amplitude resulting in fewer motor units being excited, and therefore, lower torque production at the end of the training session (25). Conversely, our findings from Day 12 provide evidence regarding increased muscular torque production as the protocol progressed indicating training-related adaptations in endurance properties such as increased number of type I muscle fibers and oxidative capacity (4, 6, 15) resulting in enhanced skeletal muscle fatigue resistance and torque maintenance. Additionally, overall PT was not statistically different between days; however, the 100% bin was higher on Day 12 than Day 1 for PT and the 100% bin was also significantly higher than the 25% bin on Day 12, suggesting a training-related decrease in involuntary muscle fatigue after training.

Significantly higher overall MT and TTI occurred during this study on Day 1 compared to Day 12, with no difference between days for overall PT. This post-training decrease in MT and TTI occurred despite higher overall stimulation intensity on Day 12. It is possible the reduced ability to maintain torque production on Training Day 12 is due to muscle accommodation to the stimulation intensity that was set to achieve a target of 15% MVC for the entire training period. Further, increasing the %MVC target torque over the course of the training period to progressively overload the muscle, in addition to gradually increasing stimulation intensity during an NMES session to recruit additional skeletal muscle fibers (27) may help overcome this accommodation and facilitate enhanced torque output after training (2). In further support, no participants reported muscle soreness, and only 1 participant reported "tiredness" in the leg prior to training Day 12. Accordingly, for this particular protocol, fatigue and inadequate muscle recovery from the previous session can likely be disregarded as reasons for lower initial torque and overall torque output on Day 12. In this case, we propose the lower overall MT and TTI on Day 12 can be attributed to muscle accommodation to the electrical stimulation intensity following the 4-week NMES training.

As with any study, there are limitations to this study. Although significant findings and meaningful effect sizes were obtained, a larger sample size would allow for analysis of sex differences. This study is also limited to the specific training protocol and stimulation parameters used; therefore, findings may not apply to other NMES protocols. The study may also be limited to healthy older adults and may not apply to other populations (e.g., individuals with orthopedic injury, individuals with neurological impairment). Future studies should incorporate a larger sample size to determine sex differences in response to an NMES training program in older adults, as well as determine the effect of a longer duration (8-12 weeks) NMES training period on involuntary torque control in older adults. Additionally, future studies should be designed to address adaptations in control of involuntary torque output resulting from NMES training in various populations (e.g., younger health adults, individuals with orthopedic injury, individuals with neuromuscular disease).

In conclusion, findings of this study support improved involuntary muscular endurance with repeated, long-term submaximal intensity NMES training, which to our knowledge has not yet been documented in the literature. The NMES training program used in this study improved muscular endurance as evidenced by increased electrically elicited torque output as the protocol progressed on the last day of training, while it decreased during the protocol on the first day of training. Also, the lower overall torque production and higher stimulation intensity required to achieve the target torque after training were likely due to muscle accommodation to the electrical current; therefore, for NMES training and rehabilitation regimens, consideration should be given for increasing the stimulation intensity during a single bout and increasing the %MVC target torque with repeated sessions to overcome accommodation. The findings of this study are important as they may assist clinicians (physical therapists, occupational therapists, athletic trainers, health and fitness professionals, etc.) and researchers when designing NMES training protocols. These findings have implications for evidence-based application of NMES designed to improve involuntary muscular endurance and for the importance of regular stimulation intensity adjustments.

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