Effect of the Simultaneous Application of NMES and HVPC on Knee Extension Torque

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Context: Electrical stimulation using simultaneous application of two current types for multiple effects is a current treatment option, but the effect of this treatment is not currently known. Objectives: To compare isometric knee extension torque when using neuromuscular electrical stimulation (NMES) in combination with High Voltage Pulsed Current (HVPC) versus NMES alone during three contraction conditions of quadriceps. Design: Counterbalanced, within-subjects design to test independent variables, stimulation protocol, and contraction condition; ANOVA to analyze dependent variable, peak torque. Setting: Athletic Training Research Laboratory. Participants: 14 healthy subjects (7 male and 7 female, age = 21.9 ± 2.0 yr, height = 173.4 ± 10.1 cm, weight = 76.1 ± 16.7 kg). Intervention: Participants performed three contraction conditions during two stimulation protocols. Main Outcome Measure: Peak isometric knee extension torque. Results: The main effect for Stimulation Protocol was not significant: $F_{1,26} = .01, P = .94$. Conclusion: Simultaneous application of HVPC with NMES does not facilitate the neuromuscular response but may provide an efficient treatment when managing atrophy, strength loss, pain, and edema associated with reconstructive surgery. Key Words: rehabilitation, electrical stimulation, quadriceps, MVIC, strength testing

Electrical stimulation is commonly used in rehabilitation of orthopedic injuries. Several types of electrical currents are available, each with different indications. With conventional treatments these currents are provided with separate treatment protocols. To provide a more efficient treatment, the OrthoDx™ (Rehabilicare, New Brighton, MN) was designed to allow the simultaneous application of two types of electrical stimulation: neuromuscular electrical stimulation (NMES) and high voltage pulsed current (HVPC). NMES is used to minimize atrophy and strength loss associated with post-surgical immobilization$^{1,2}$ while HVPC is a form of electrical stimulation that may be of benefit for reducing edema$^{3-6}$ and pain.$^{7,8}$

One of the limiting factors when using NMES is the patient’s tolerance to the intensity of the electrical current.$^{9,10}$ Belanger et al$^9$ found that the discomfort experienced with NMES was reduced by 50% when cutaneous pain was eliminated through nerve block. Miller and Webers$^{11}$ applied this concept and found...
subjects tolerated greater current and subsequently produced significantly greater torque when ice massage was used prior to NMES. Cutaneous pain was eliminated through nerve block in the first study\(^9\) and lessened with ice in the second study.\(^{11}\) In each study, the area of skin treated was beneath the stimulating electrodes. It is possible that peak torque will increase with the simultaneous application of HVPC and NMES due to the pain suppression characteristics of the HVPC. If HVPC lessens the level of discomfort experienced during NMES, then a greater current intensity could be comfortably tolerated when using NMES. The greater intensity should correspond to a more forceful contraction, which would ultimately result in improved neuromuscular benefits. Therefore, the purpose of this investigation was to compare the effect of a protocol using NMES in combination with HVPC versus NMES alone on knee extension torque during different contraction conditions.

Many of the studies that have used electrical stimulation for the development of strength have reported the percentage of maximum voluntary isometric contractions (MVIC) that are achieved through electrical stimulation. So that the results of this study could be compared to those in the literature, a secondary purpose was to compare the NMES induced contractions without voluntary effort, and MVIC superimposed with NMES induced contractions, to the torque of MVIC.

**Methods**

**Design**

This study used a counterbalanced, within-subjects design to test the independent variables, stimulation protocol (NMES with HVPC or NMES only) and contraction condition: (1) MVIC, (2) MVIC superimposed with NMES induced contraction, and (3) NMES induced contraction without voluntary effort. The dependent variable was peak torque.

**Subject Information**

Fourteen healthy subjects (7 male and 7 female, age = 21.9 ± 2.0 yr, height = 173.4 ± 10.1cm, weight = 76.1 ± 16.7 kg) without previous knee injury who had not been treated with NMES volunteered to participate in this study. Participants reported to an athletic training research laboratory on the first day of testing where they were informed of the potential risks of the study and provided signed consent. The university’s institutional review board approved the study.

**Interventions**

Subjects performed isometric knee extension exercises under three contraction conditions: (1) MVIC, (2) MVIC superimposed with NMES induced contraction (superimposed), and (3) NMES induced contraction without voluntary effort (involuntary). Three repetitions were completed under each condition with 30 seconds rest between repetitions (30 seconds was the longest rest time available on the electrical stimulator). Subjects received each stimulation protocol (NMES with HVPC or NMES only) on separate occasions using a within subjects design. The treatment order was counter-balanced and test sessions were 48-72 hours apart.
An OrthoDx™ provided the two types of electrical stimulating currents through separate channels. The unit can be powered by batteries or through an AC adaptor but to insure a consistent power source the AC adaptor was used. The stimulation specifications that were provided by the manufacturer are listed in Table 1.

The right anterior thigh of each subject was shaved and the skin cleaned with isopropyl alcohol wipes. For the treatment that included HVPC, three sets of electrodes were affixed to each subject according to manufacturer recommendations and the electrodes were connected to the OrthoDx™ through separate leads. A 4” × 6.75” electrode was centered on the anterior thigh midway between the anterior superior iliac spine and the superior pole of the patella over the motor point for the rectus femoris. This electrode served as an active electrode for the NMES current and a dispersive electrode for the HVPC. A 4” × 2” electrode was placed diagonally over the motor point of the vastus medialis oblique, which served as the second active electrode for the NMES current. Four 2” × 2” electrodes were placed below the knee and served as the active electrodes for the HVPC. Two were placed on the anterior leg, 3” below the center of the patella and two on the posterior leg, 2” below the popliteal crease (Figure 1). For the NMES only condition, the active HVPC electrodes were not used.

<table>
<thead>
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<th>Table 1  Electrical Stimulation Specifications</th>
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<tr>
<td><strong>Parameters</strong></td>
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<tr>
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<tr>
<td>intensity</td>
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<td>pulse rate</td>
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<td>duty cycle</td>
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<td>polarity</td>
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**Figure 1** — Electrode placement for the HVPC and NMES currents. The proximal pad is shared by the two currents.
During the combination treatment condition, the HVPC was used with NMES but the unit was turned off during MVIC. The HVPC was activated two minutes before each NMES condition. Intensity just below the motor threshold was selected by increasing the intensity until a visible contraction and then decreasing the intensity until no contraction was seen. A maximum comfortable intensity was used for all NMES. Maximum comfortable intensity was defined as the highest intensity that did not cause pain. Subjects were not asked to tolerate painful stimulation intensities. To find the maximum comfortable intensity, the voltage was gradually increased until subjects reported a sensation, further until a muscular response was noted, and further until the intensity became uncomfortable. The intensity was then reduced until the uncomfortable intensity was eliminated. This process was repeated for each of the two NMES conditions but the intensity was not altered between individual repetitions. The intensity was reset before the second NMES condition to account for accommodation to the current so that a maximum comfortable intensity was consistently used.

After a standard warm-up that included elliptical cycling, quadriceps stretching, and submaximal contractions, subjects were positioned on a Kin-Com® 125E Plus (Chattanooga Group, Inc., Hixon, TN) with hip flexion angle of 80° and knee flexion angle of 70°. The axis of rotation of the dynamometer was aligned to the anatomical axis of the right knee. To ensure reliable measurements, the dynamometer was calibrated, all stabilization straps were used to prevent unwanted movement, subjects’ hands were required to remain free, and no visual feedback was provided during testing (Figure 2).

**Outcome Measures**

Peak torque was recorded with the dynamometer while isometric muscle actions were performed under each condition for ten seconds. For condition 1, subjects were asked to extend the knee against the fixed lever arm of the dynamometer with maximum force. For condition 2, subjects were asked to extend the knee with maximum effort when electrical stimulation was perceived. For condition 3, subjects were asked to relax and allow the knee to extend against the fixed lever arm without voluntary effort.

![Figure 2](image) — Subject positioned on the Kin-Com™ with knee in 70° flexion.
Statistical Analyses

The largest peak torque produced under each condition was recorded for analysis. Data normalized for body weight were analyzed with a 2 (Stimulation Protocol) × 3 (Contraction Condition) ANOVA with repeated measures.

Results

The main effect for Contraction Condition was significant, $F_{2,52} = 289.1, P < .0001$. Post hoc analysis with Duncan’s Multiple Range Test showed that contraction condition 3 (involuntary) yielded significantly less torque than contraction conditions 1 (MVIC) and 2 (superimposed). The main effect for Stimulation Protocol was not significant, $F_{1,26} = .01, P = .94$. A post-hoc power analysis provided an effect size of 0.25 and power of 0.38. This result suggests no difference between the two stimulation protocols under any of the contraction conditions (Figure 3). The Stimulation Protocol × Contraction Condition interaction was not significant, $F_{2,52} = .46, P = .63$. A post-hoc power analysis provided an effect size of 0.25 and power of 0.11. The mean torques produced during NMES with HVPC were $1000.1 \pm 167.4$, $1015.0 \pm 191.1$, and $430.4 \pm 121.2$ Nm and during NMES only were $1033.8 \pm 194.0$, $1007.7 \pm 150.2$, and $414.1 \pm 134.0$ Nm for conditions 1 (MVIC), 2 (superimposed), and 3 (involuntary), respectively (Figure 4). This finding shows that any differences in contraction condition were consistent across both stimulation protocols. An important practical result is the percentage of MVIC produced when contracting under the stimulation conditions. When using NMES with HVPC, the superimposed contraction produced 101.5% of the MVIC and the electrically induced contraction without voluntary effort produced 43% of the MVIC. When using only the NMES current, the superimposed contraction produced 97.5% of the MVIC and the NMES induced contraction without voluntary effort produced 40.0% of the MVIC.

Figure 3 — Knee Extension Torque (Nm; Mean ± SD) under the NMES and HVPC and NMES alone stimulation protocols for the three contraction conditions. Comparison of contraction conditions resulted in a significant difference (*indicates significance: $F_{2,52} = 289.1, P < .0001$). Post hoc analysis showed that Involuntary < MVIC and superimposed.
Discussion

Electrical stimulation serves several purposes in post surgical rehabilitation. In orthopedic and sports medicine, the most critical of these would seem to be neuromuscular development. Restoring muscular strength and decreasing atrophy during early rehabilitation when voluntary exercise is limited is a critical function of electrical stimulation. NMES has been shown to increase strength\textsuperscript{12-20} and to be as effective as voluntary exercise in healthy subjects.\textsuperscript{21-27} When training deficient muscle after reconstructive surgery, the combination of NMES with voluntary exercise has been shown to be more effective than voluntary exercise alone.\textsuperscript{28-31} NMES has also been shown effective in decreasing atrophy associated with post surgical immobilization when used alone\textsuperscript{32} and in combination with isometric exercise.\textsuperscript{31}

Protocols using the simultaneous application of the two currents are currently being used in rehabilitation following reconstructive knee surgery; however, the effect of these protocols on the resulting contraction torque is not currently known. Therefore, the primary purpose of our study was to assess simultaneous application of HVPC and NMES on knee extension torque. With this protocol the active electrodes for HVPC are placed around the knee to reduce pain and edema. It was hypothesized that the HVPC, which serves to decrease pain, would allow the patient to comfortably tolerate a greater current intensity. These results did not support our hypothesis, however. The statistical analysis revealed no difference in contraction torque when NMES was used with HVPC versus NMES alone. Because the protocol used to deliver the simultaneous application of these two currents is relatively new, there is little literature on this specific topic. Therefore, explaining the results is difficult and we are forced to speculate.

Two potential explanations for the lack of support for the hypothesis are offered. First, there may be a difference in the effect that HVPC has on the discomfort associated with electrical current and the pain associated with reconstructive knee surgery. In this case, the HVPC could be effective in managing post-surgical pain but have no effect on the discomfort associated with NMES. Secondly, HVPC may
have had no pain relieving effect for the affected musculature. We speculate that the location of pain relief with the electrode arrangement recommended by the manufacturer may be more specific to the knee joint as opposed to the musculature receiving electrical stimulation. The active electrodes for the HVPC were placed distal to the knee while the greatest discomfort during NMES was reported in the area of the VMO.

A secondary but equally important purpose of our study was to compare the torque of NMES induced contractions to MVIC. NMES induced contractions were reported as a percentage of MVIC so that these results could then be compared to the literature. Because there were no differences between NMES in combination with HVPC and NMES alone, the results of the combined currents will be used when comparing these results to those of previous studies.

When comparing contraction torques across studies, a distinction between maximum tolerable and maximum comfortable stimulation intensities must be made. The majority of the studies identified in the literature that reported contraction torques used maximum tolerable intensities.\textsuperscript{6,18,22-24,32-42} In these studies, the average contraction torques varied tremendously with initial intensities ranging from 10 to 93% of MVIC.\textsuperscript{18} In one study, late in the training session, the average contraction torque actually exceeded the original MVIC and was reported at 110%. In each case, the subjects were reported to be healthy and in several cases, trained athletes. Even though healthy subjects were used in our study, the protocol tested is specifically recommended for post-surgical rehabilitation. It is unlikely that patients recovering from reconstructive surgery would accept intensities that are defined in the literature as maximum tolerable. Therefore, the more clinically relevant maximum comfortable stimulation intensity was chosen for our study.

The literature review revealed fewer studies that used maximum comfortable intensities. When maximum comfortable intensities were used in previous studies, the average contraction torque was between 20 and 42% of MVIC,\textsuperscript{2,26,32,35,43,44} whereas in our study the average contraction torque was 43% of MVIC. Direct comparison of the torque production in our study to other studies is difficult because so many variables are different. The results of our study, however, compare favorably to the literature when like intensities are compared.

Contraction torque is an important consideration because several investigators have suggested a minimum percentage of MVIC is required for strength development. For healthy subjects, the required overload has been estimated to be greater than 60% of MVIC.\textsuperscript{23,45} Soo et al\textsuperscript{19} showed that a training intensity of 50% was sufficient to significantly increase strength when ten training sessions were used, however. Miller and Thepaut-Mathieu\textsuperscript{40} suggested the minimum intensity that must be achieved during a majority of the training sessions was only 33%. The importance of training intensity has also been demonstrated in injured subjects. Snyder-Mackler et al\textsuperscript{46} used a regression analysis to show a direct relationship between training intensity and recovery of muscular strength after ACL reconstruction. In addition, the analysis showed an apparent minimum threshold of 10% of MVIC is required for a training effect. Based on the literature, it appears that a maximum comfortable stimulation intensity use in our study, which produced a training intensity of 43%, is sufficient to increase strength in patients recovering from reconstructive surgery. Therefore, the treatment protocol used in our study can be recommended for neuromuscular restoration because forceful contractions were produced while
a current thought to reduce edema\textsuperscript{3-6} and pain\textsuperscript{7,8} was also provided. Further research using post-operative patients is recommended to test the overall effectiveness of this protocol. A summary of studies reporting contraction torque during maximum comfortable intensities when using NMES is provided in Table 2.

MVIC were also compared to MVIC superimposed with NMES induced contractions. This technique is recommended because it will theoretically lead to an increase in the number of muscle fibers that are recruited. This is a result of the difference in the order of recruitment with voluntary exercise versus electrical stimulation. With voluntary exercise, Type I muscle fibers are recruited first and if the contraction requires greater force, the recruitment of Type II muscle fibers will follow. With electrical stimulation, the recruitment order is opposite thus there is selective recruitment of type II muscle fibers.\textsuperscript{47,48} These fibers are innervated by larger nerve fibers than type I muscle fibers. The larger fibers have a lower resistance to electrical current and are therefore recruited first during electrical stimulation.\textsuperscript{49} Therefore, a superimposed contraction should result in greater total fiber recruitment through selective recruitment of both Type I and Type II fibers. Several studies have supported this theory with superimposed contractions that exceeded 100\% of MVIC,\textsuperscript{6,24,25,39,50} yet an equal number of studies failed to support this theory with superimposed contractions that failed to exceed 100\%.\textsuperscript{6,23,36,38,43} The average superimposed contraction torque during the combined electrical stimulation in our study was 101.5\% of MVIC, which was not significantly different from MVIC. Therefore, the results of our study did not support the contention that MVIC superimposed with NMES induced contractions are more forceful than MVIC.

During our study, we noticed that the decrease in torque across three repetitions was greater with NMES (20.5\%) than with MVIC (6.8\%). With both conditions, it is likely that fatigue played a role in the decrease in torque. The greater decrease in torque with NMES may be attributed to accommodation to the electrical current and fatigue of Type II muscle fibers, which tend to be recruited in higher proportions during electrically induced contractions. This is an important consideration because contraction torque is related to strength gains. If the decreased torque is due to fatigue, then longer rest intervals are warranted when training with NMES. If accommodation is the cause of the decreased torque, however, an increase in the stimulation intensity across repetitions is warranted. Further research should directly compare torque across repetitions with various rest intervals when performing voluntary versus involuntary muscle actions.

**Conclusion**

1. No significant differences in torque during knee extension were found when comparing NMES in combination with HVPC versus NMES alone.
2. The average force of contraction of 43\% of MVIC produced when NMES was combined with HVPC should be sufficient to increase strength in deficient muscle after reconstructive surgery.
3. Combining HVPC with NMES does not facilitate the neuromuscular response but may provide an efficient treatment when managing atrophy, strength loss, pain, and edema associated with reconstructive surgery.
<table>
<thead>
<tr>
<th>Author</th>
<th>Muscles and Joint Angle</th>
<th>Current Type</th>
<th>Electrodes: Size and Placement</th>
<th>Subjects</th>
<th>NMES only % MVIC</th>
<th>Superimposed % MVIC</th>
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<tr>
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<td>Russian</td>
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<td>Hartsell35</td>
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<td>Knee Extensors 105° Flexion</td>
<td>Russian</td>
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<td>Biphasic</td>
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<td>Healthy male and female</td>
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*Note.* Rectus Femoris (RF), Vastus Lateralis (VL), Vastus Medialis Oblique (VMO)
References


