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# The Acute Effects of Patterned Electrical Neuromuscular Stimulation on Quadriceps Torque Production and Motor Unit Recruitment

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Master of Science

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ABSTRACT

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BACKGROUND: Electric muscle stimulation (EMS) has been widely used in the rehabilitation of musculoskeletal injuries. Patterned electrical neuromuscular stimulation (PENS), a specific form of EMS, has been developed to better educate muscles to contract properly. The physiological efficacy of PENS has not been quantifiably identified. OBJECTIVES: The aim of this study is to determine the acute effect of one PENS training session (3 sets of 10 1-sec repetitions) on maximal isometric knee extensor (MVIC) torque production and surface EMG (sEMG) in healthy nonathlete college students. DESIGN: A randomized repeated-measures design was used in this study. METHODS: Twenty-two male college students participated in the study. All participants completed two training sessions, one with PENS and one without, in a randomized crossover design. RESULTS: One bout of PENS training significantly increased MVIC (3.1% ± 1.7%, $p = 0.03$) which was greater than the change in MVIC of the control group ($p = 0.03$). Control training did not alter MVIC but resulted in significant decrease in average sEMG amplitude (-7.8% ± 1.6%, $p \leq 0.01$) and peak sEMG amplitude (-10.4% ± 2.7%, $p \leq 0.01$). These reductions in sEMG following control training were significantly different from the PENS group ($p = 0.03$ and $p \leq 0.01$). CONCLUSIONS: The findings suggest that strength training in conjunction with PENS can enhance torque production after just one bout of training. The increase in torque with no change in sEMG amplitude can be explained by increased motor unit synchronization or decreased cocontraction of antagonist muscles.

Keywords: patterned electrical neuromuscular stimulation (PENS), maximum voluntary isometric contraction (MVIC), motor unit recruitment, median frequency, synchronization

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## INTRODUCTION

Electric muscle stimulation (EMS), or the elicitation of muscle contraction using electric impulses, has been used since the mid-1900's in applications such as pain control,[5] strength training,[3] and neuromuscular rehabilitation.[21, 27, 32] Common forms of EMS include neuromuscular electrical stimulation (NMES),[20] transcutaneous neuromuscular electrical stimulation (TENS),[10] and functional electrical stimulation (FES).[33] The electrical stimulus parameters (current intensity, pulse frequency, pulse duration, etc.) of these EMS modalities are specifically designed to achieve optimal outcomes. However, all forms of EMS are thought to recruit muscle fibers in an inverse pattern from that which occurs during normal voluntary muscle contraction.[14] The recruitment of larger diameter motor units during EMS, however, may provide some benefit to patients when combined with normal voluntary contractions.[12]

One of the newest developed systems of EMS is called patterned electrical neuromuscular stimulation (PENS). The electrical stimulus parameters of PENS have been designed to mimic the motor unit firing pattern of skeletal muscles in healthy individuals during voluntary contraction.[15] One assumed outcome of combining PENS with voluntary muscle contractions in untrained and/or injured patients is that the PENS trained muscle will "learn" the firing pattern associated with "trained" muscle.

In two case studies using PENS training,[25, 26] patients suffering from hemiplegia and torticollis demonstrated improved active range of motion, decreased spasticity and reduced pain with contraction alterations that indicate a change in neuromuscular control. Six wks of combined PENS and jump training[15] improved vertical jump by 9.7 percent compared to jump training alone (2.0 percent). Physiological adaptations (muscle size or motor unit recruitment patterns) that would account for the increase in vertical jump height were not measured.

The capacity of the peripheral nervous system, specifically the neuromuscular junction, to adapt and be remodeled in response to motor unit activity has been clearly shown by Witzemann et al.[37] NMES training either with or without concurrent voluntary muscle contraction provides an effective means of altering motor unit recruitment and preferentially training high threshold motor units.[35] While the vast majority of EMS training studies have been evaluated using a multiweek training program.[4, 6, 8, 23, 36, 41] Recent research suggests that improved neuromuscular function can be achieved following a single bout of EMS training. Keser et al.[19] demonstrated improved ankle dorsiflexion angles during the swing phase of gait in patients with foot-drop following a single bout of EMS training. Furthermore, Zahn et al.[40] demonstrated that increased alpha motor neuron activity can lead to increased expression of neurotrophin in the motor endplate region. Increased expression of neurotrophin is known to enhance neuromuscular junction activity and neuromuscular efficiency.[9, 16, 18] Preliminary studies in our laboratory indicate that a single bout of PENS treatment can increase maximal knee extension torque production and reduce surface EMG amplitude in healthy, yet untrained subjects. As such, it was the aim of this study to determine the impact of a single bout of PENS treatment on muscle force production and if the increase in force production is associated with an increase in neuromuscular efficiency. Under our experimental procedures we defined an increase in neuromuscular efficiency following training as either no change in force production with a decrease in sEMG amplitude or an increase in force production with no change in sEMG amplitude. We tested the hypothesis that a single bout of PENS treatment would acutely increase force production and that this increase in force production would be associated with a reduction in motor unit recruitment as measured by sEMG activity.

## METHODS

### Experimental Design

This study followed a pretest/posttest crossover design (Table 1). Healthy individuals were recruited to participate in one orientation session and two different training sessions involving knee extensor exercise with or without concurrent PENS. Prior to participation the subjects provided written informed consent. The study was approved by the university's institutional review board (IRB) for the protection of human subjects. All subjects were relatively untrained and did not participate in more than 3 h of physical training (workouts, participation in sports, running, etc.) per week. Volunteers were excluded if they had a lower extremity musculoskeletal injury within the past 3 mo that required medical consultation. In addition, all subjects were free of any pain to the lower extremity that might limit normal strength and function. The subjects were randomly assigned to perform either PENS training first or control training first. All training sessions were separated by 1 wk.

### Procedures

Orientation session (Table 2): Following a 5-min warm-up on a stationary bike the subjects were prepped and fitted for the stimulating and measurement electrodes. Subjects sat in the Biodex Dynamometer chair and, after shaving and cleaning two 2" x 4" areas on the quadriceps, 2 new reusable PENS electrodes (Accelerated Care Plus, Reno, NV) were placed on the proximal-lateral aspect of the thigh and the distal-medial aspect of the thigh (Figure 1). An OmniStim FX2 (Accelerated Care Plus, Reno, NV) unit was used to deliver the PENS treatment and control treatment. The PENS treatment parameters consisted of an asymmetrical biphasic square waveform at a frequency of 50 Hz. The phase duration of PENS lasted 100 msec with stimulus trains at 200 μsec. An sEMG measurement electrode was placed on the distal vastus

lateralis (VL) parallel to the predicted path of muscle fibers 8–12 cm superior and slightly lateral to the patella. A common reference electrode was placed over the patella. Surface electromyography was recorded using an adhesive tri-electrode (Delsys, Boston, MA). Surface EMG signals were amplified 500 times, filtered (band-pass at 10 and 500 Hz), and sampled at 200 samples/sec. The EMG recordings were rectified and analyzed to determine the average and peak sEMG amplitude and median discharge frequency during all contractions.

Isometric knee extension torque and sEMG were measured on the dominant leg with subjects seated in the chair of a Biodex Dynamometer (System 3, Biodex Medical Systems, Shirley, NY) with the chair setting at 120° and the knee at 90° with a torque sampling rate of 100 Hz (Figure 2). The axis of the dynamometer was aligned with the lateral epicondyle or axis of rotation of the participant's knee joint. The arm of the dynamometer was adjusted parallel to the anterior aspect of the tibia, with the lower edge of the padded strap positioned approximately 3 cm proximal to the lateral malleolus. The trunk, waist and thigh were stabilized using straps on the Biodex Dynamometer chair.

Each subject performed 7 1-sec MVICs to practice attaining their maximal voluntary force. All repetitions within each set for both training and testing were separated by 15 sec. Subjects also practiced performing a 1-sec isometric contraction at 60 percent of their MVIC. Subjects performed 7 practice repetitions in order to maintain a torque at 60 percent MVIC (+/- 10 percent). The first 4 repetitions were voluntary contractions without PENS and the last 3 were done in conjunction with PENS. Subjects practiced synchronizing their voluntary contractions with the PENS system auditory signal that occurred 500 msec prior to the electrical stimulation for each repetition. The primary difference between Control and PENS training

groups was the amplitude of electric stimulation delivered (140 mA for PENS training and 1 mA for Control training).

Training sessions (Tables 3 and 4): Prior to each training session 3 MVIC's with sEMG were recorded. Participants were provided with visual feedback of their torque production via a computer monitor and received verbal encouragement to promote maximal performance during each MVIC. The average peak torque produced from the 3 repetitions was recorded as the subject's MVIC. Sixty percent of this MVIC was used during the training portion.

The subjects then took part in a 15-min training session with or without PENS. The training protocol consisted of 3 sets of 10 repetitions at approximately 60 percent of MVIC with each set separated by 2 mins. Visual feedback via the torque generation on the Biodex monitor was supplied during the contractions to ensure the repetitions stayed within the 50-70 percent MVIC range. Five mins following the last training set a posttest MVIC and sEMG was recorded in the same manner as the pretest.

**Data Analysis**

Peak torque was determined from the mean of the three MVIC contractions performed during the pre- or posttreatment sessions. Surface EMG data was smoothed using the root mean square (rms) of the signal (sEMGrms). All sEMGrms signals were normalized to the pretest sEMGrms of the training session. The average and peak sEMGrms amplitudes were determined from the average sEMGrms data from the three MVIC contractions performed pre- and posttreatment.

The change in sEMGrms amplitude alone does not discriminate between changes in both motor unit recruitment or synchronization.[38] We used the median frequency (MF) of the power spectral density (PSD) curve to provide a quantitative assessment of the EMG spike frequency.

An increase in recruitment of fast twitch motor units is reflected in an increase in the MF of the PSD.[31] The change in sEMGrms amplitude and MF between the pretest and posttests for PENS and Control treatments was evaluated using covariate repeated measures ANOVA. The covariates were pretest levels of the measured variable and the order of treatment presentation.

**RESULTS**

Table 1 shows the pretest and posttest mean values for MVIC, average sEMG amplitude, peak sEMG amplitude, and MF from the PSD plot for Control and PENS treatments. MVIC increased 3.1 percent ± 1.7 percent ($p = 0.04$) following PENS treatment and was significantly greater than the Control group response ($p = 0.03$) (Table 5). The Control group's MVIC was unchanged by the treatment ($p = 0.3$). In response to PENS treatment the surface sEMG recording was unchanged (average sEMGrms amplitude, peak sEMGrms amplitude, or MF, Table 5). In contrast, we noted a 7.8 percent ± 1.6 percent reduction in average sEMG amplitude ($p \leq 0.01$) and a 10.4 percent ± 2.7 percent decrease in peak sEMG amplitude ($p \leq 0.01$) following the Control treatment. These reductions in average and peak sEMGrms amplitudes were significantly greater than the changes in the PENS group ($p = 0.03$ and $p \leq 0.01$, respectively). The MF of the PSD curve was unaltered by either PENS or the Control treatment.

The change in MVIC following PENS or Control treatment was weakly correlated with the change in average sEMGrms amplitude ($r^2 = 0.33$, $p \leq 0.01$, $n = 44$) and peak sEMGrms amplitude ($r^2 = 0.17$, $p \leq 0.01$, $n = 44$). Overall, less than 33 percent of the variation in MVIC following PENS or Control treatment can be accounted for by variation in the sEMGrms amplitude.

**DISCUSSION**

This study demonstrated that a single bout of isometric training combined with PENS resulted in an increase in maximal voluntary leg extension torque. A single bout of training without PENS did not alter MVIC of the knee extensors. The increase in MVIC with PENS training was not associated with a change in the sEMGrms amplitude or median frequency. In contrast, a single bout of training without PENS resulted in a decrease in average and peak sEMGrms amplitude despite generating the same absolute torque, an indication of increased neuromuscular efficiency. While we identified a weak correlation between MVIC and average sEMGrms amplitude (Figure 3) this relationship accounts for less than 33 percent of the improvement in MVIC response in the PENS treatment. Thus, the majority of the improvement in MVIC with PENS training is likely associated with some other neuromuscular adaptation.

It is generally accepted that muscle strength and power are determined by muscle size and the characteristics of the motor neural drive. During the first several wks of resistance training, prior to muscle hypertrophy, adaptation to neural drive plays the biggest role in strength gains.[34] Three key aspects of neuromuscular efficiency, namely: motor unit recruitment, median firing frequency and motor unit synchronization, provide important insight into the progression of strength gains during training and/or rehabilitation.

Torque or force is normally found to be positively correlated with the magnitude of motor unit recruitment, as reflected in an increase in average sEMGrms amplitude.[28] We postulated three possible explanations for the observed increase in torque production following PENS training in the absence of a change in sEMG properties (amplitude or MF). Because these two parameters did not change following PENS treatment, we propose that the increase in MVIC was due to an increase in motor unit synchronization. First, in this study, motor unit recruitment and

firing rate were indirectly measured through the sEMG collection (sEMG amplitude and MF). Therefore we postulate that the concomitant delivery of PENS and voluntary contraction might lead to higher synchronization of activated motor units. DeLuca et al.,[11] suggested that typically synchronous firing of motor units would only happen sporadically in humans and therefore will not typically contribute significantly to increased force production during a maximal voluntary contraction. However, Milner-Brown et al.,[24] demonstrated motor unit synchronization in the first dorsal interosseus muscles following resistive exercise training protocol. The validity of this observation was originally questioned because of their use of sEMG to describe motor unit activity.[39] More recently Semmler and Nordstrom[30] measured motor unit activation of the first dorsal interosseous directly with intramuscular EMG electrodes and observed increased motor unit synchronization in strength trained subjects. In their crosssectional study the degree of motor unit synchronization was lowest in untrained control subjects, was higher in skilled musicians, and highest in strength trained subjects. In the present study, we noted a change in the relationship between MVIC and the sEMGrms amplitude for both training groups. In the control group, 1 bout of training without PENS caused a decrease in sEMGrms amplitude while maintaining a similar MVIC. A single bout of isometric training with PENS increased MVIC without a significant change in sEMGrms amplitude. It is our supposition that the increase in neuromuscular efficiency following PENS training is primarily due to increased motor unit synchronization.

A second possible mechanism to obtain strength improvements in the absence of increased neural drive would be to reduce inhibitory afferent signals to the spinal cord and/or motor cortex. PENS treatment produces rhythmic EMS that is precisely timed with the normal voluntary muscle contraction. Afferent signaling influenced during PENS might manipulate the

ensuing efferent plan and result in less inhibition of recruitment of motor units. MacKay-Lyons[22] described the importance of these specialized neural circuits as a collection of sensory/ motor nerves and interneuron's that influence movement patterns. Adaptation to input-output properties of many possible proprioceptors (golgi tendon, muscle spindle, interneurons) may result in disinhibition and an increased expression of muscle force.[17] Aagaard et al.[2] found that autogenic inhibitory feedback to the spinal motorneuron pool was decreased as a result of heavy resistance strength training. We speculate that afferent signals related to muscle loading and proprioception could also play a role in decreasing inhibitory signals to the spinal cord in the PENS group which would help explain the increased torque production.

Finally, a reduction of the coactivation of antagonist muscles during an MVIC following resistive exercise may contribute to a reduction in sEMG and/or an increase in force production.[13, 29] There is some crosstalk between EMG signals of agonist and antagonist muscles during recorded voluntary contraction. Reduced coactivation of antagonist muscles during knee extension MVIC may slightly decrease the sEMGrms of the vastus lateralis; though previous researchers have found that the contribution of antagonist sEMG signals to a recorded agonist are negligible.[1] Carolan et al.[7] definitively demonstrated a reduction in antagonist coactivation in response to resistive training. They showed that an 8-wk strength training program increased MVIC of the knee extensors by 32.8 percent with no significant change in SEMG activity of the vastus lateralis. The antagonist muscle (biceps femoris) noted a minimal decrease from 14.9 percent to 11.5 percent of maximal sEMG. This supports the notion that the lower MVIC-to-sEMG ratio following PENS or Control training is not likely due to changes in the sEMG recording of the cocontracted antagonist. All these possible interpretations are tempered slightly by the weak correlation between ΔMVIC and Δ average sEMGrms amplitude (Figure 1).

However, the weak association between ΔMVIC and Δ average sEMGrms amplitude ($r^2 = 0.33$) indicates that something other than an increase in Δ average sEMGrms amplitude must account for 67 percent of the increase in MVIC following PENS training.

One limitation of this study was the inability of sEMGrms data to definitively identify neuromuscular adaptations such as motor unit synchronization. However, the remarkable increase in MVIC within 5 min of PENS training provides a foundational idea to explain the phenomenon and impetus to focus on the impact of longer term PENS training on neuromuscular adaptations using more direct EMG procedures.

**CONCLUSION**

In the current study, a single bout of isometric training with PENS acutely increased muscle torque production without a major change in sEMG recording, an indication of increased neuromuscular efficiency. Since the median discharge frequency during voluntary MVIC was also unaltered, our interpretation of these data are that the contraction involved an increase in motor unit synchronization, interaction of PENS with muscle afferents leading to disinhibition, and/or a reduction in coactivation of antagonist muscles. Based upon our findings we expect long term exercise and/or rehabilitation programs with PENS will enhance overall neuromuscular function and force production in healthy adults. Because PENS training has shown promise in improving neuromuscular function in specific disease states,[25, 26] it is likely PENS training may also facilitate muscle rehabilitation in patients with a variety of clinical conditions.

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Table 1 - Research Design

| Independent Variables | Dependent Variables |
|---|---|
| **2 Groups** | **MVIC Torque Production** |
| - PENS Training | |
| - Control Training | |
| **Time** | **sEMG Data** |
| - Pretest | - Motor Unit Recruitment |
| - Posttest | - Firing Rate |

Table 2 - Training Session 1 Procedures

| **Time in min** | **Session 1 Procedures** |
|---|---|
| 1-5 | Paperwork and Descriptors |
| 6-10 | Warm-up |
| 11-15 | Attach PENS and Dynamometer |
| 16-18 | Practice MVICs (7 repetitions) |
| 19-21 | Practice 60% MVIC (4 voluntary and 3 with PENS) |
| 22-25 | Detach PENS and Dynamometer |

Table 3 - Training Session 2 Procedures

| **Time in min** | **Session 2 Procedures** |
|---|---|
| 1-5 | Warm-up |
| 6-10 | Attach EMG, PENS, Dynamometer |
| 11-13 | Practice MVICs (7 repetitions) |
| 14-16 | Practice 60% MVIC (7 repetitions) |
| 17-21 | Rest |
| 22-24 | Pretest MVIC (average of 3 Reps) |
| 25-29 | Rest |
| 30-49 | PENS Training (140 mA at 60% MVIC) or Control Training (01 mA at 60% MVIC) |
| 50-54 | Rest |
| 55-57 | Posttest MVIC (average of 3 Reps) |
| 58-65 | Detach EMG, PENS, Dynamometer |

Table 4 - Training Session 3 Procedures

| **Time in min** | **Session 3 Procedures** |
|---|---|
| 1-5 | Warm-up |
| 6-10 | Attach EMG, PENS, Dynamometer |
| 11-13 | Practice MVICs (7 repetitions) |
| 14-16 | Practice 60% MVIC (7 repetitions) |
| 17-21 | Rest |
| 22-24 | Pretest MVIC (average of 3 Reps) |
| 25-29 | Rest |
| 30-49 | PENS Training (140 mA at 60% MVIC) or Control Training (01 mA at 60% MVIC) |
| 50-54 | Rest |
| 55-57 | Posttest MVIC (average of 3 Reps) |
| 58-65 | Detach EMG, PENS, Dynamometer |

Table 5 - Quantitative Results

| | Control | | | PENS | | |
|---|---|---|---|---|---|---|
| Variable | PRE | POST | Δ | PRE | POST | Δ |
| MVIC, N•meters | 285 ± 12 | 281 ± 14 | -4 ± 3† | 285 ± 14 | 293 ± 15* | 9 ± 5 |
| Average sEMG amplitude, µvolts | 169 ± 17 | 156 ± 16* | -13 ± 3† | 162 ± 14 | 165 ± 15 | 3 ± 5 |
| Peak sEMG amplitude, µvolts | 353 ± 33 | 316 ± 29* | -37 ± 9† | 329 ± 30 | 349 ± 30 | 20 ± 14 |
| Median sEMG frequency, Hz | 122 ± 5 | 122 ± 5 | 0 ± 2 | 117 ± 4 | 119 ± 4 | 2 ± 2 |

MVIC, maximal voluntary isometric contraction; Values are Mean ± 1 SEM for n = 22 subjects

*$p < 0.05$ different from Pre

†$p < 0.05$ Δ different between Control and PENS

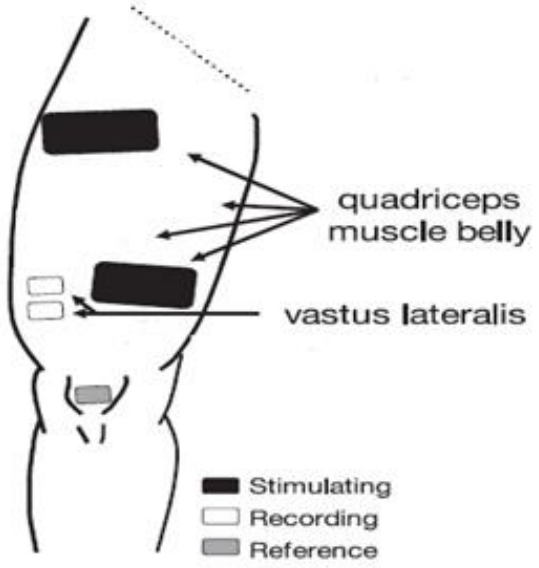


Figure 1. EMG electrode array

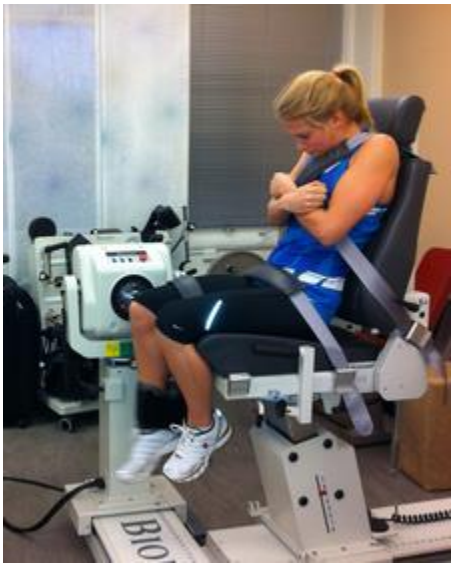

Figure 2. Position of patient during training and testing

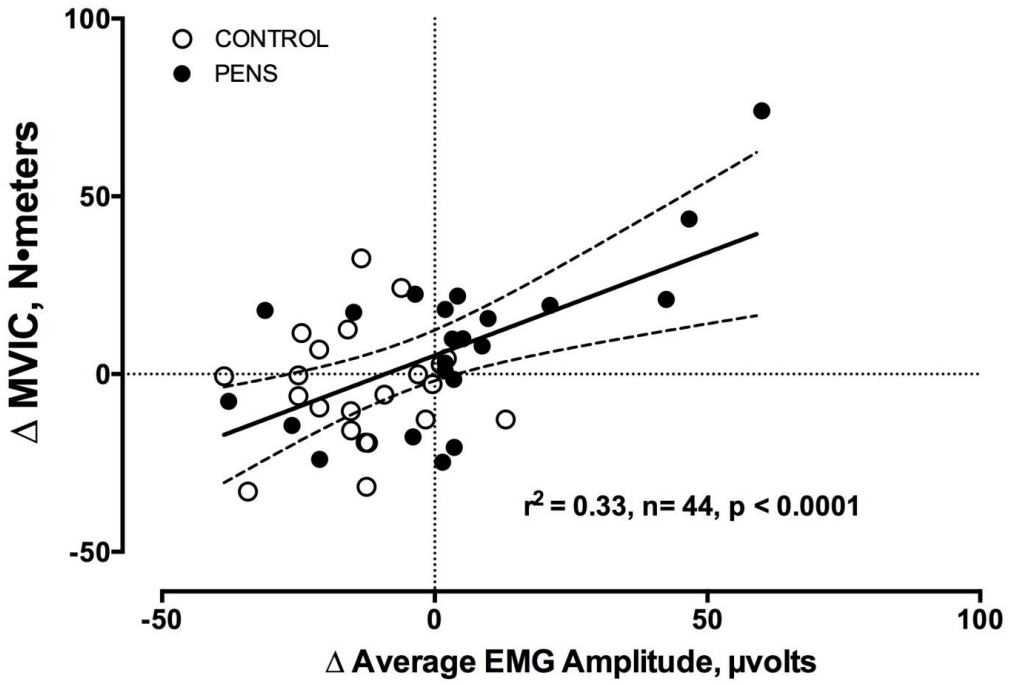


Figure 3. The correlation between the difference in average surface electromyography (sEMG) amplitude and maximal voluntary isometric contraction (MVIC) torque production of the knee extensor muscles (lateral quadriceps)