

UNIVERSITY OF WISCONSIN-LA CROSSE

Graduate Studies

THE EFFECTS OF NEUROMUSCULAR ELECTRICAL STIMULATION ON
ABDOMINAL STRENGTH AND ENDURANCE, AND CORE STRENGTH

A Manuscript Style Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Clinical Exercise Physiology

Julie A. Olson

College of Science and Health
Clinical Exercise Physiology

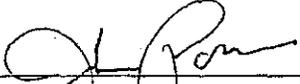
December, 2014

THE EFFECTS OF NEUROMUSCULAR ELECTRICAL STIMULATION ON
ABDOMINAL STRENGTH AND ENDURANCE AND CORE STRENGTH

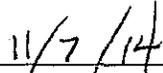
By Julie A. Olson

We recommend acceptance of this thesis in partial fulfillment of the candidate's requirements for the degree of Master of Science in Clinical Exercise Physiology.

The candidate has completed the oral defense of the thesis.



John Porcari, Ph.D.
Thesis Committee Chairperson



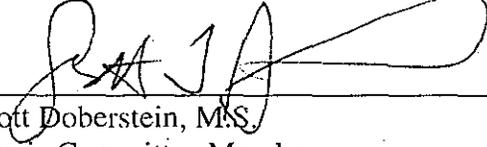
Date



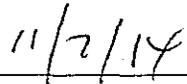
Carl Foster, Ph.D.
Thesis Committee Member



Date



Scott Doberstein, M.S.
Thesis Committee Member

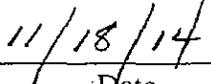


Date

Thesis accepted



Steven Simpson, Ph.D.
Graduate Studies Director



Date

ABSTRACT

Olson, J.A. The effects of neuromuscular electrical stimulation on abdominal strength and endurance, and core strength. MS in Clinical Exercise Physiology, December 2014, 23pp. (J. Porcari)

The study was designed to evaluate the effects of self-administered neuromuscular electrical stimulation (NMES) on changes in abdominal muscle strength and endurance and core strength. Fifty-three adults were randomly assigned into high intensity (HI: n=27) or low intensity (LI: n=26) groups. The NMES device for the LI group had been altered so that subjects felt some tactile sensation, but the intensity was not sufficient to elicit a muscular contraction. All subjects stimulated their abdominals 5 days per week (30 minutes per session) for 6 weeks and refrained from engaging in any additional abdominal exercises during the study. Subjects were tested at baseline, 2, 4, and 6 weeks. The HI group had a significantly greater increase in strength at 4 weeks (19%) and 6 weeks (29%) compared to the LI group. The HI group completed more curl-ups than the LI group at 2 weeks (62%) and 4 weeks (118%). Both groups had a significant increase in core strength over the course of the study, with no difference between groups. Results of the current study indicate that high intensity NMES can significantly increase abdominal strength and endurance compared to LI intensity (control) stimulation.

TABLE OF CONTENTS

	PAGE
LIST OF TABLES.....	v
INTRODUCTION.....	1
METHODS.....	4
Subjects.....	4
Procedures.....	5
Testing.....	5
Abdominal Strength.....	5
Abdominal Endurance.....	5
Core Strength.....	6
Training.....	6
Data Analysis.....	7
RESULTS.....	8
Abdominal Muscle Strength.....	9
Abdominal Muscle Endurance.....	10
Prone Plank Test.....	10
DISCUSSION.....	12
Conclusions.....	15
REFERENCES.....	17

LIST OF TABLES

TABLE	PAGE
1. Descriptive characteristics of the subjects who completed the study (N=53).....	9
2. Change in Biodex strength (N·m) for both groups over the course of the study.....	9
3. Change in curl-ups completed for both groups over the course of the study.....	10
4. Change in prone plank time for both groups over the course of the study.....	11

INTRODUCTION

Neuromuscular electrical stimulation (NMES) is a well-established therapeutic modality that has been used for many years in the practice of physical therapy. When traditional exercise is not possible due to injury or surgery, NMES may be used as a means of maintaining muscular strength and minimizing atrophy due to immobilization (Hainaut and Duchateau, 1992). In the 1960's, Kots (1977) reported using NMES as a training adjunct with elite athletes in the former Soviet Union and reported strength improvement of 30- 40%. He suggested that NMES might be more effective than volitional exercise for strength improvement.

In recent years, fitness equipment companies have marketed NMES devices for healthy individuals as an alternative way to improve muscle strength and endurance and improve body composition. These devices are designed for many different muscle groups, but are of particular interest for the abdominal region. The desire of Americans to have a trim waist and flat stomach without having to exercise is an attractive option for many people.

There are conflicting results regarding the effects of NMES on the abdominal musculature. Many studies have demonstrated significant improvements in abdominal strength and endurance, perceived muscle tone, and body satisfaction following NMES training (Alon et al., 1987; Alon et al., 1992, Abendroth-Smith and Sword, 1977; Anderson et al., 2006, Ballantyne and Donne, 1999; Caulfield et al., 2002; Cullinane et

al., 2002; Porcari et al., 2005), while others have shown no improvement in these parameters (Aikman, et al., 1985; Porcari et al., 2002).

Whether or not improvements in muscular strength and endurance are seen with NMES is reasonably dependent upon the strength of the resulting contraction. Those studies that have utilized contractions in excess of 60% of maximum voluntary contraction (MVC) have shown positive benefits (Currier and Mann, 1983; Maffiuletti, 2002; Selkowitz, 1989; and Soo et al., 1988). Many over-the-counter NMES devices do not deliver a strong enough stimulus to reach this threshold. We (Porcari et al., 2002) investigated the effects of training with Body Shapers, a commercially available NMES device, on the strength of various muscle groups, body composition, and physical appearance. No statistically significant improvements in any of the outcome measurements were found. The conclusion of the study was that the stimulator and electrodes used to deliver the stimulation were poorly constructed and did not deliver a strong enough current to elicit a contraction of sufficient strength to induce gains in strength. Additionally, the stimulation was very uncomfortable for subjects. Measures taken during stimulated contractions suggested that the percentage of maximal strength that the muscles were contracting was less than 20% of MVC.

In an attempt to overcome this deficiency and elicit stronger muscular contractions, Bio-Medical Research, Ltd. (Galway, Ireland) developed the Slendertone® FLEX, which is an NMES device that targets the abdominal muscles. The FLEX delivers an electrical current to the abdominal region using medical-grade adhesive pads placed over motor units of the abdominal musculature. Based upon the results of two studies conducted by the manufacturer (Caulfield et al., 2002; Cullinane et al., 2002), the

Slendertone® FLEX is cleared by the FDA to increase the strength and tone of the abdominal muscles. Data from our laboratory (Porcari et al., 2005) supported these claims, as abdominal strength improved 49% and abdominal endurance increased 72% compared to a non-stimulation control group. There was an increase in perceived muscle tone in all subjects in the stimulation group and a significant reduction in abdominal girth. A criticism of the above study was that the control group did not receive any intervention. Thus, it was felt that some of the improvement in the stimulation group, particularly regarding subjective outcome measures, was attributable to the placebo effect.

Bio-Medical Research, Ltd. has developed a newer NMES device called the Slendertone® System Abs belt, which has the same indications for use as the Slendertone® FLEX, but with higher intensity levels and more user-friendly controls. These higher intensities are purported to generate stronger, more effective muscle contractions. The purpose of this study was to determine the efficacy of the Slendertone® System-Abs belt for increasing abdominal muscular strength and endurance and improving core muscle strength in healthy, middle-aged adults.

METHODS

Subjects

Fifty-six adult volunteers from the La Crosse, Wisconsin area were recruited through an advertisement in the local newspaper. Inclusion criteria required the subjects to be between 25 and 55 years old, to be healthy by their own report, to have a body mass index (BMI) between 18 and 30, and not to have been involved in any type of formal abdominal training program within the previous 6 months. In addition, subjects with any implanted medical devices (pacemaker, pump, catheter, etc.), insertion or removal of an intrauterine contraceptive device (i.e. coil) within the previous month, or who were currently pregnant or had given birth in the previous three months were excluded. Subjects were randomly assigned into one of two groups: a high intensity treatment group (HI) or a low intensity treatment group (LI). Group assignment was randomized and training was double-blinded. Both groups were instructed not to alter their diet or engage in any additional exercise over the course of the 6-week study period.

All subjects gave written informed consent prior to participating in the study and the protocol was approved by the Institutional Review Board for the Protection of Human Subjects at the University of Wisconsin-La Crosse. Subjects received a \$200 honorarium and a Slendertone® System-Abs belt at the conclusion of the study.

Procedures

Testing

All subjects completed an identical battery of tests at baseline and at 2, 4, and 6 weeks of the study protocol. Testing included a determination of abdominal muscle strength, abdominal endurance, and core muscle strength. All tests were given in the same order for all subjects.

Abdominal Strength

Abdominal strength was measured by having the subject perform five isometric contractions using an isokinetic dynamometer (Biodex, USA). The subject rested supine on a movable bench in a bent-knee position. The lever arm of the isokinetic dynamometer was set parallel with the ground (180 degrees) and the padded extension arm was placed just below the nipple line on the lower third of the sternum. The height of the bench was adjusted for each subject so that the extension arm remained at 180 degrees. Each subject was given several practice trials to make sure the position of the lever arm was comfortable on their chest. Subjects then performed five maximal isometric contractions, with 30 seconds rest between repetitions. The average torque measurement of the highest two repetitions was used in the analysis.

Abdominal Endurance

Abdominal endurance was assessed using the American College of Sports Medicine (ACSM) paced curl-up test (ACSM, 2000). The subjects were in a supine position on a mat with the knees bent to 90 degrees (measured with a goniometer). The subject's arms were at the side, palms facing down, with the middle fingers touching a piece of tape. A second piece of tape was placed 8 cm (for those who were ≥ 45 years) or

12 cm (for those who were <45 years) from the first piece of tape. The subject's shoes remained on during the test. The individual completed slow, controlled curl-ups to lift the shoulder blades off the mat (trunk makes a 30-degree angle with the mat) in time with a pre-recorded tape at a pace of 40 curl-ups per minute. The subject performed as many curl-ups as possible without pausing. The test was terminated when the subject could no longer keep up with the pace of the audio tape or their fingers could not reach the second piece of tape.

Core Strength

Core strength was measured using the Prone Plank test (Quinn, 2008). Subjects assumed the prone "plank" position, with full body weight supported only by the forearms and toes. Their body was straight with the elbows parallel to each other and directly under the shoulders. They held this "plank" position for a period of 60 seconds. At the end of the 60 second period, the subjects successively raised each limb individually for a period of 15 seconds each. They then were to raise their right arm and left leg for 15 seconds then their left arm and right leg for 15 seconds. Upon completion of the limb movements, the subjects returned to the plank position for 30 seconds. These series of movements were continued until the subject could no longer continue or was no longer able to maintain a straight body position. The total hold time was measured for each subject.

Training

All subjects underwent stimulation five times per week for six weeks. Each session was 30 minutes in duration. The NMES device used in the current study was the Slendertone® System-Abs belt. The belt used three pre-gelled electrodes to deliver an

electrical current to the abdominal region. The HI group used the stimulation belt that is currently on the market. The LI group used the same belt, but the stimulator had been altered so that the electrical current was strong enough to cause some tactile sensation, but was not strong enough to elicit a visible muscular contraction. Both groups used program number 3 on the stimulation controller.

Each subject was given an individual orientation session, during which they were supervised for their first stimulation session. All other stimulation sessions were completed on their own. Subjects in both groups were encouraged to use the highest tolerable level on their stimulator to achieve the strongest possible contractions. Subjects recorded the maximum intensity reached during each stimulation session in a training log.

Data Analysis

Standard descriptive statistics were used to characterize the subject population. Changes in abdominal isometric muscle strength, abdominal endurance, and core muscle strength were analyzed using a 3-way ANOVA with repeated measures (Group X Gender X Time Point). Since there were no differences in the responses of male and females, data were collapsed across gender. Data were then analyzed with a 2-way ANOVA with repeated measures (Group X Time Point). When there was a significant F ratio, Tukey's post-hoc tests were used to isolate pair-wise differences. Alpha was set at 0.05 to achieve statistical significance for all analyses.

RESULTS

Fifty-three of the original 56 subjects successfully completed the study. One member of the LI group withdrew from the study due to dissatisfaction with the training intensity delivered by the attenuated device and another subject in the LI group was disqualified for doing additional sit-ups during the study period. One subject in the HI group was withdrawn from the study after experiencing heavier than usual blood flow during menses. For the final analysis there were 27 subjects in the HI group (14 male and 13 female) and 26 subjects in the LI group (12 male and 14 female). Descriptive characteristics of the subjects who completed the study are presented in Table 1. There were no significant differences between groups at the start of the study for any of the outcome measures.

Table 1. Descriptive characteristics of the subjects who completed the study (N=53).

Group	Age (yr)	Height (cm)	Weight (kg)	BMI
High Intensity				
Males	39.7(8.0)	178.3(6.4)	79.8(7.7)	25.2(2.4)
Females	39.5(9.8)	161.9(5.6)	62.1(5.5)	23.7(1.9)
Overall	39.6(8.7)	170.4(10.2)	71.3(11.2)	24.5(2.2)
Low Intensity				
Males	37.3(9.0)	178.0(8.1)	82.7(8.6)	26.2(2.6)
Females	40.7(8.2)	168.7(6.6)	72.3(7.3)	25.4(2.3)
Overall	39.1(8.6)	173.0(8.6)	77.1(9.4)	25.8(2.4)

Values represent mean and (standard deviation)

Abdominal Muscle Strength

The isometric strength for each group at each time point is summarized in Table

2. The HI group had a significant increase in strength at weeks 4 and 6 and these improvements were significantly greater than the LI group.

Table 2. Change in Biodex strength (N·m) for both groups over the course of the study.

Group	Baseline	Week 2	Week 4	Week 6
High Intensity	143.3(30.3)	155.0(25.7)	170.8(29.5) ^{ab#}	184.3(32.0) ^{abc#}
Low Intensity	143.1(21.1)	142.9(19.0)	145.9(20.9)	148.6(19.6)

Values represent mean and (standard deviation)

^a Significantly different than Baseline (p<0.05)

^b Significantly different than Week 2 (p<0.05)

^c Significantly different than Week 4 (p<0.05)

[#] Change for the HI group is significantly different than the change for the LI group at the same time point (p<.05)

Abdominal Muscle Endurance

Curl-up performance of the two groups is summarized in Table 3. The HI group had a significant improvement in curl-up performance after 2, 4, and 6 weeks compared to baseline. Additionally, the improvement at each testing point was significantly different than the preceding testing period. There was no significant increase for the LI group across the 6-week study. Changes between groups were statistically significant at weeks 2 and 4.

Table 3. Change in curl-ups completed for both groups over the course of the study.

Group	Baseline	Week 2	Week 4	Week 6
High Intensity	42(41)	69(84) ^{a #}	104(148) ^{ab#}	144(210) ^{abc}
Low Intensity	45(40)	46(36)	52(46)	78(75)

Values represent mean and (standard deviation)

^a Significantly different than Baseline (p<0.05)

^b Significantly different than Week 2 (p<0.05)

^c Significantly different than Week 4 (p<0.05)

[#] Change for the HI group is significantly different than the change for the LI group at the same time point (p<0.05)

Prone Plank Test

Changes in prone plank test performance (seconds) are presented in Table 4.

Overall there was a significant improvement in core strength. However, there was not an interaction between group and time, suggesting that the improvement in core strength was comparable for both groups over the course of the study.

Table 4. Change in prone plank time for both groups over the course of the study.

Group	Baseline	Week 2	Week 4	Week 6
High Intensity	74.8(31.0)	81.4(33.0)	92.5(32.5)	94.5(31.6)
Low Intensity	83.8(33.0)	91.1(34.3)	92.1(21.2)	97.3(29.5)

Values represent mean and (standard deviation)

DISCUSSION

The present study found 19% and 29% gains in abdominal strength after 4 and 6 weeks of high intensity stimulation, respectively. These results are in line with results from other studies that have used EMS to stimulate the abdominal musculature (Alon et al., 1987; Alon et al., 1992; Ballantyne and Donne, 1999). The results of Alon et al. (1987) and Alon et al. (1992) are virtually identical to those of the current study, as they found increase of 20.8% and 19.6%, respectively, after 4 weeks of EMS training. Since Alon's studies were both 4 weeks in duration comparisons beyond that point are not possible.

The magnitude of the strength improvements seen in the current study are less than those reported previously in our laboratory using a Slendertone® product (Porcari et al., 2005). In the current study a 19% improvement was apparent after 4 weeks, compared to a 34% strength increase in the earlier study after the same amount of time. In the previous study strength improvement was not measured at 6 weeks; however, using linear extrapolation, improvement would have been approximately 46%, compared to 29% in the current study. It has been suggested that in the earlier study a greater number of training sessions were supervised, which may have led to increased compliance with the treatment protocol; hence greater strength improvement. However, the device used in the current study recorded the frequency of stimulation sessions as well as the peak stimulation level used during each session. Attendance to the number of training sessions for every individual in the study was exactly as prescribed (5 sessions per week

for 6 weeks). Peak intensity was slightly lower in the current study versus the earlier study. However, since the available intensity of the stimulator used in the current study (Slendertone® System-Abs) was stronger than that used in the previous study (Slendertone® FLEX), the intensity of the achieved contractions were assumed to be similar.

The HI group had significantly greater improvements in abdominal endurance at weeks 2 and 4 compared to the LI group. The data at week 6 also indicated a strong but non-significant trend in favor of the HI group. Due to the large standard deviation of scores, the difference was not statistically significant at that time point, however. The percentage increases in the HI group at 2, 4, and 6 weeks were 64%, 133%, and 243%, respectively, compared to 2%, 15%, and 73% for the LI group at the same time points. The difference in improvement between the HI and LI groups were 62%, 118%, and 170% at weeks 2, 4, and 6. The magnitude of the net improvement for the HI group in the current study was larger than previously found in our laboratory (Porcari et al., 2005). When looking at the raw data, it was observed that two male subjects in the HI group did 575 and 600 curl-ups at the 4-week time period. These same individuals did 800 and 797 curl-ups, respectively, at the 6-week testing mark. As these curl-ups for these individuals were conducted according to protocol, their data was included in the final analysis. Had the data for these two individuals been removed from the data set, the net improvement between the HI and LI groups at weeks 4 (the only comparable testing time between the two studies), would have been 40% in favor of the HI group. This is comparable to the 49% improvement seen in the previous study at the same time point.

Another thing to point out was that the LI group had a 15% improvement in curl-up performance at the 4 – Week testing time and a 73% improvement at the 6 – Week testing point. In the previous study by Porcari et al. (2005), a passive control group (no stimulation) had a 28% improvement in curl-up performance after 8 weeks. This would indicate that there is learning effect associated with performance of the curl-up test. However, the magnitude of the improvement over time, coupled with the fact that the subjects in the current study were receiving some stimulation, even though it was at a very low level, suggests that the LI group may have had some improvement in muscular performance. Consistent with this finding is the report of Alon et al. (1997) of a 14% increase in strength when subjects received very low levels of abdominal electrical stimulation (just enough to elicit a visible tetanic contraction) for 3 hours per day. Another possibility is that because tests like the curl-up test are effort dependent, improvements may have reflected an increased effort on the part of subjects. If they felt that the belt was providing a benefit, they may have tried harder during the later testing sessions.

Results for core strength testing showed improvements for both groups at each measurement point. The HI group improved 18% after 6 weeks and the LI group improved 12% over the same time frame. Since the prone plank test is a novel test for most people, performance on the test depends a great deal on technique and balance. It is plausible that the overall improvement reflected an improvement in technique, which may have masked any therapeutic difference that may have existed between the groups.

The design of the present study sought to achieve an optimal compromise by providing the control group with an identical device to the treatment group, but which

operated at a much lower intensity. That lower intensity was selected such that it would give a strong sensory sensation, but minimal apparent muscle contraction. Research experience with EMS indicates that to gain muscle strength, the stimulation should typically induce at least 30% of MVC (Mueller, 1959). Hence the treatment intensity for the control group was selected to be well below this threshold. The compromise in design with respect to a true sham treatment is that there may have been some residual therapeutic benefit which did not depend on the generation of large forces in the muscle. Alon et al. (1997) studied the effects of very low-intensity, long-duration (3 hour) electrical stimulation on the strength and endurance of the abdominal muscles in a randomized controlled study of 38 subjects. They found a 14% increase in abdominal strength after 4 weeks in the treatment group, whereas the control group did not change. While the low intensity group in the present study only used the device for 30 minutes per day, there may have been some neurological training effect leading to their improved ACSM curl-up performance and improvement in subjective measures.

Conclusions

High intensity electrical muscle stimulation to the abdominal musculature resulted in greater improvements in abdominal muscular strength and endurance compared to low intensity (control) stimulation. The non-significant improvements in abdominal endurance and core strength in the LI group were thought to be due to a learning effect associated with the tests performed, the placebo effect, or a combination of both factors. It is also possible that these results could have been due to the fact that the LI group was receiving a very low level of electrical stimulation, which could have caused some positive neuromuscular changes. Additionally, future studies may want to compare the

potential benefits of traditional abdominal exercises vs. NMES applied to the abdominal musculature.

REFERENCES

- Abendroth-Smith, J. and Sword, K. (1977) Toning and strengthening predominant muscle groups through electrical muscle stimulation. *Medicine and Science in Sports and Exercise* **29**, 5.
- Aikman, H.D., Majerus, J.J., Van Wart, K.W., Barr, J.O. and Cook, T.M. (1985) Effects of electrical stimulation vs. sit-ups on abdominal strength and endurance. *Physical Therapy* **65**, 596.
- Alon, G., Frederickson, R., Gallagher, L., Rehwoldt, C.T., Guillen, M., Putnam Pement, M.L. and Barhart, J.B. (1992) Electrical stimulation of the abdominals: The effects of three versus five weekly treatments. *Journal of Clinical Electrophysiology* **4**, 5-11.
- Alon, G., McCombe, S.A., Koutsantinis, S., Stumphauzer, L.J., Burgwin., K.C., Parent, M.M. and Bosworth, .A. (1987) Comparison of the effects of electrical stimulation and exercise on abdominal musculature. *The Journal of Orthopaedic and Sports Physical Therapy* **8**, 567-573.
- Alon, G. and D.J. Taylor (1997) Electrically elicited minimal visible tetanic contraction and its effect on abdominal muscles strength and endurance. *European Journal of Physical Medicine and Rehabilitation* **7**, 2-6.
- American College of Sports Medicine (2000) ACSM's Guidelines for Exercise Testing and Prescription. 6th Edition. Lippincott Williams & Wilkins, Philadelphia.
- Anderson, A.G., Murphy, M.H., Murtagh, E. and Nevill, A. (2006) An 8-week randomized controlled trial on the effects of brisk walking, and brisk walking with abdominal electrical stimulation on anthropometric, body composition, and self-perception measures in sedentary adult women. *Psychology of Sport and Exercise* **7**, 437-451.
- Ballantyne, E. and Donne, B. (1999) Effects of neuromuscular electrical stimulation on static and dynamic abdominal strength and endurance in healthy males. *Sports Sciene*, 431.
- Balogun, J.A., Onilari, O.O., Akeju, O.A. and Marzouk., D.K. (1993) High voltage electrical stimulation in the augmentation of muscle strength: Effects of pulse frequency. *Archives of Physical Medicine and Rehabilitation* **74**, 910-916.

- Caulfield, B., Cullinane, C., White, C. and Monique, C. (2002) The effects of CSI electrical muscle stimulation on strength of the quadriceps femoris and hamstring muscles and on body satisfaction: A controlled study. *Unpublished*, Bio-Medical Research Institute, Dublin, Ireland.
- Cullinane, C., Caulfield, B., Monique, C. and White, C. (2002) The effects of CSI electrical muscle stimulation of the abdominal muscles and walking on body image and abdominal muscle strength. *Unpublished*, Bio-Medical Research Institute, Dublin, Ireland.
- Currier, D.P. and Mann, R. (1983) Muscular strength development by electrical stimulation in healthy individuals. *Physical Therapy* **63**, 915-921.
- Hainaut, K. and Duchateau, J. (1992) Neuromuscular electrical stimulation and voluntary exercise. *Sports Medicine* **14**(2), 100-113.
- Kots, Y. (1977). Electrostimulation of skeletal muscles. *Canadian-Soviet Exchange Symposium*, Concordia University.
- Maffiuletti, N.A., Dugnani, S., Folz, M., Di Pierno, E. and Mauro, F. (2002) Effect of combined electrostimulation and plyometric training on vertical jump height. *Medicine and Science in Sports and Exercise* **34**, 1638-1644.
- Mueller, E.A. (1959) Training muscle strength. *Ergonomics* **2**, 216-222.
- Porcari, J.P., Palmer McLean, K., Foster, C., Kernozek, T., Crenshaw, B. and Swenson, C. (2002) Effects of electrical muscle stimulation on body composition, muscle strength, and physical appearance. *Journal of Strength and Conditioning Association Research* **16**, 165-172.
- Porcari, J.P., Miller, J., K. Cornwell., Foster, C., Gibson, M., McLean, K. and Kernozek, T. (2005) The effects of neuromuscular electrical stimulation training on abdominal strength, endurance, and selected anthropometric measures. *Journal of Sports Medicine and Science* **4**, 66-75.
- Quinn, E. (2008) Core muscle strength and stability test.
http://sportsmedicine.about.com/od/bestabexercises/a/core_test.htm
- Selkowitz, D.M. (1989) High frequency electrical stimulation in muscle strengthening. *American Journal of Sports Medicine* **17**, 103-111.
- Soo, C.L., Currier, D.P. and Threlkeld, A.J. (1988) Augmenting voluntary torque of healthy muscle by optimization of electrical stimulation. *Physical Therapy* **68**, 333-337.