The effects of neuromuscular electrical stimulation on skeletal muscle architecture and qualitative properties in vivo

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ABSTRACT

The purpose of this study was to evaluate the changes in skeletal muscle architecture and qualitative properties by muscle contraction force when neuromuscular electrical stimulation (NMES) of 50% MVIC was applied. Sixteen subjects (8 male, 8 female) without neuromuscular disease volunteered to participate in the study. All subjects were divided into two subgroups: control (no electrical stimulation) group and 50% maximal voluntary isometric contraction (MVIC) group. NMES training program was performed in the calf muscle three times a week for 10 weeks. Before and after the experiments, the MVIC of ankle plantar flexor was measured by the use of dynamometer, and the ultrasonography in the gastrocnemius medialis muscle was measured. The following results were obtained; MVIC was significantly increased in the electrical stimulation groups. Pennation angle, muscle density, and white area index also considerably changed in the electrical stimulation groups. In conclusion, the NMES training of 50% MVIC, comparative low level, improved the skeletal muscle architecture and the qualitative properties as well as the muscle contraction force.

Keywords: *Skeletal muscle architecture, Pennation angle, Muscle density, Neuromuscular electrical stimulation*

1. INTRODUCTION

Neuromuscular electrical stimulation (NMES) therapy has often been used for muscle strengthening, endurance, and control of edema after injury. Moreover, NMES has been frequently used as an efficient tool to increase strength in healthy humans [1]. Currier and Mann (1983) [2] reported that NMES training of 67% of the maximum voluntary isometric contraction (MVIC) resulted in a 14% increase in the MVIC of the quadriceps femoris after completing 3 sessions per week over a 5-week period. Kubiak et al. (1987) [3] reported that the use of a training intensity of 45% of the MVIC resulted in a 33% increase in isometric quadriceps femoris force. Recently, NMES has also been utilized in clinical settings for motor coordination recovery improvement in patients with central nervous system damage [4] and for pain reduction in patients with osteoarthritis [5]. Gondin et al. (2006) [6] demonstrated that the enhancement of the neuromuscular function has been mainly ascribed to neural adaptations and reported that the NMES training-induced neural adaptations were maintained after detraining, This finding suggests that neural changes are long-lasting. Also, recent studies have shown that resistance training may enhance the muscle weakness associated with aging [7], [8].

With noninvasive medical imaging technology, such as ultrasonography, it has become possible to measure human skeletal muscle architecture in vivo [9]. Jensen et al. (1998) [10] reported that quantitative ultrasonography seems to be a potential clinical examination method to detect tissue composition of myalgic muscles compared to healthy muscles. Ultrasound is reflected differently by the varying tissue components, and its resulting images show the muscle tissues as dark, whereas the bones and connective tissues appear bright [11].

The architecture of a skeletal muscle has been defined as the geometric arrangement of the fascicle within the muscle [12]. Muscle architecture is mainly characterized by the fascicle length, the pennation angle and muscle thickness [13]. In pinnate muscles, fascicles are arranged obliquely with respect to the tendon, and this angulation (pennation angle) is altered by contractions [14]. Reeves et al. (2004) [8] reported that pennation angle during maximal contraction increased by 13% after resistance training. Narici et al. (2003) [15] found a decrease in pennation angle and fibre length with aging.

However, the change of the muscle architecture and qualitative properties by the NMES is not completely known. The purpose of this study was to look for the change of skeletal muscle architecture and qualitative properties by muscle contraction force when NMES was applied.

2. MATERIALS AND METHODS

2.1 General overview of the experimental design

The skeletal muscle architecture and qualitative properties

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were assessed before and after 10-weeks where subjects were asked to maintain their normal physical activity patterns. The subjects were randomly assigned to either a control group or a NMES group.

2.2 Subjects

Sixteen health subjects participated in the study (Table 1). Exclusionary criteria included any preexisting peripheral nerve dysfunction, musculoskeletal disorders, and cardiopulmonary disorders. Each subject had not participated in any other form of systematic physical training for at least 10 weeks prior to the beginning of the study. The subjects were excluded from the study if they had a significant ankle injury, or had a contraindication to the use of neuromuscular electrical muscle stimulation.

Table 1. Characteristics of the subjects

	Control (4 male, 4 female)	50% MVIC (4 male, 4 female)	Total (n=16)
Age (years)	22.50±1.69	22.50±1.85	22.50±1.71
Weight (kg)	69.38±8.44	52.81±5.17	58.03±11.35
Height (cm)	167.38±9.13	172.13±10.11	169.75±9.62

All value are shown as mean±SD.

2.3 Measurement of maximal voluntary isometric contraction

Maximal voluntary isometric contraction (MVIC) of the left plantarflexor muscle was recorded using a dynamometer (CS200, JLW, USA). The subjects were seated in a straight leg position trying to isolate the non-dominant gastrocnemius muscle as the primary torque generator. Their chests and hips were strapped to avoid accessory movements. The center of the ankle joint was aligned with the dynamometer center of rotation at an angle of 90° (zero degrees of plantar flexion). The subjects performed 3 MVICs prior to the first week of electrical stimulation training, and prior to weeks 5, 9 of training. The final MVIC measurements were taken following the 10 weeks of training. The subjects were asked to give maximal effort during each isometric contraction and were given verbal encouragement throughout the MVIC test. Each MVIC measurement was followed by a 2-minutes rest.

2.4 Measurement of muscle architecture

The non-dominant gastrocnemius medialis muscle architecture was examined in vivo using real-time B-mode ultrasonography (SONOACE 6000, Medison, Korea), with a 40-mm, 7.5MHz linear-array probe. Scan was taken in the midsagittal and longitudinal plane, at the 50% of the gastrocnemius medialis muscle length. The probe was coated with a water-soluble transmission gel to provide acoustic contact. Using Adobe Photoshop CS (Adobe, USA), a representative rectangle of the gastrocnemius medialis muscle ultrasonography image was selected (Fig. 1, 2), after calibration of the digitally stored echo image (332x310 pixels, 8-bit grey value). Image pro plus 4.5 (Media cybernetics Inc, USA) was used for digital image analysis.

2.4.1 Measurement of the pennation angle: To measure pennation angle, the ultrasound probe was placed over the gastrocnemius medialis muscle in longitudinal plane. Pennation angle was defined as the angle between the fascicular path and the deep aponeurosis of the gastrocnemius.

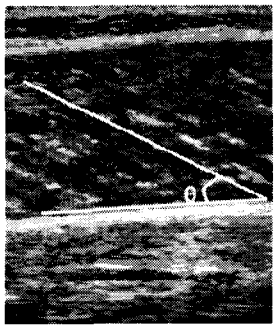

Fig. 1. Measurement of the pennation angle

2.4.2 Measurement of qualitative property: Echogenicity was measured in the midsagittal plane. To quantify muscle echogenicity, the average pixel value ("density") of the selection was determined [16]. If this value was 0, the selection was pure black; if this value was 255, the selection was pure white. The white areas are determined by all pixels with a value larger than 190, which corresponds to selecting visible contrasts. The white area index is calculated as pixel number of the white area in the selection divided by the total pixel number of the selection.

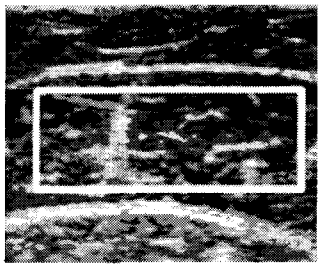

Fig. 2. Measurement of muscle density and white area index

2.4.3 Electrical stimulation training program: The control group did not receive electrical stimulation. The subjects in the group treated with NMES received 3 electrical stimulation sessions per week for 10 weeks. The electrical stimulator (Myomed 932, Enraf Nonius, Netherlands) was used to stimulate the non-dominant gastrocnemius muscle. The electrical stimulation was on 10 seconds and off for 40 seconds of each minute and had a frequency of 34 bursts per second with a carrier frequency of 2,500 Hz. The carbon-impregnated silicon rubber electrodes (6cm×8cm) were placed over the surface of the gastocnemius muscle. The electrode was attached on the gastrocnemius muscle by bipolar placement. The average muscle contraction produced during the NMES session was 50% of the MVIC.

2.5 Data analysis

Statistical analysis was performed using the SPSS 12.0 version for windows program. All values are reported as a mean ± standard error (S.E.). The difference between the groups according to the measuring periods was examined using analysis of covariance (ANCOVA). Significance level in analysis was set to α=0.05.

3. RESULTS

3.1 Effect on maximal voluntary isometric contraction: There was a significant difference between groups in the mean MVIC during the maximal voluntary isometric contraction ($p<0.001$).

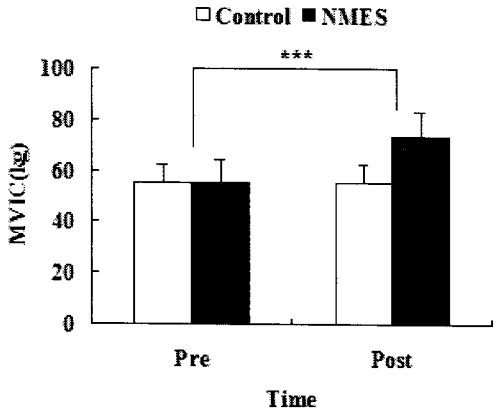

Fig. 3. The change of MVIC between groups

3.2 Effect on the muscle architecture

3.2.1 Effect on the pennation angle: There was a significant difference between groups in the mean pennation angle during the maximal voluntary isometric ($p<0.01$).

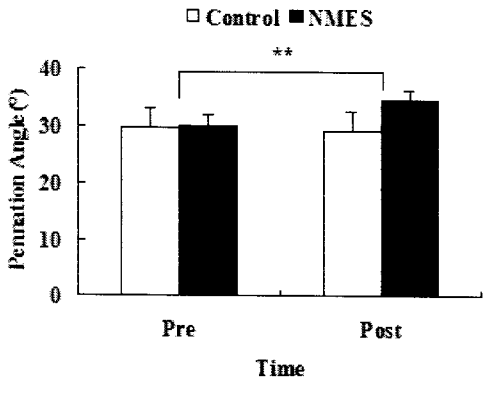

Fig. 4. The change of pennation angle between groups

3.3 Effect on the muscle qualitative property

3.3.1 Effect on the muscle density: There was a significant difference between groups in the mean muscle density ($p<0.001$).

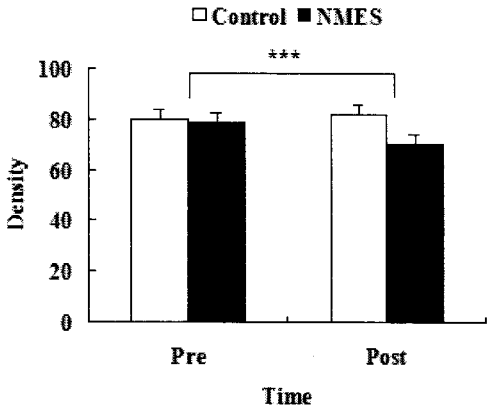

Fig. 5. The change of muscle density between groups

3.3.2 Effect on the white area index: There was a significant difference between groups in the mean white area index ($p<0.001$).

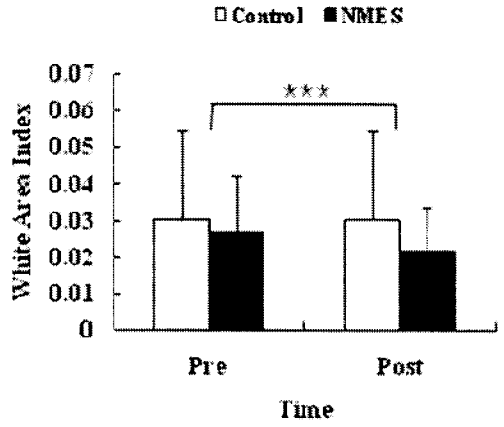

Fig. 6. The change of white area index between groups

4. DISCUSSION

Muscle architecture, together with intrinsic properties such as fiber composition, affects functional characteristics of the muscle such as its maximal force [4], [17]. Since the 1990's, a technique for determining the length and angles of fascicles in vivo humans has been developed.

Gondin et al. (2006) [6] reported that after NMES training (about 60% of the MVC) for 5 weeks, the MVC of the ankle plantar flexor increased significantly by 22%. This study showed that the MVC of the ankle plantar flexor increased by 26% after NMES training. Our study showed that the NMES training of 50% of the MVIC for 10 weeks produced an improved MVC. This is to demonstrate a good improvement in relation to the electrical stimulation level with the NMES training. A higher level of the electrical stimulation causes a

pain more than a lower level of the electrical stimulation. This study also showed that the pennation angle during MVIC increased by 4° after the NMES training. In a similar study to our results, training caused significant changes in muscle architecture [15] and the pennation angle of triceps brachii muscle increased by 4.8° after resistance training during for 16 weeks [18]. Reeves et al. (2004) [8] reported that altered architectural features were the unique muscular adaptations occurred in response to the training. The pennation angle and fascicle length are determinants of force production [19], which are modified according to the functional demands [12]. Therefore, our results from these studies showed that muscle resistance training influenced the muscle architecture such as the pennation angle.

Ultrasound technology provides quantitative and qualitative information about muscle features that may be lined to measures of muscle strength [20]. Maurits et al. (2003) [16] reported that muscle density and white area index increased strongly with age in healthy controls. Also, the study reported that age-related deterioration of muscle tissues was present in the same degree in both biceps and quadriceps muscle and that the increased density, inhomogeneity and white area index seen with age imply all age-related replacement of muscle mass by fat and collagen. Sipila and Suominen (1996) [21] suggested that the decrease of ultrasound imaging echo intensity after training was because of a decreased proportion of the fat in the muscle. Thus, the ultrasound echo pattern of the images seems to be related to the muscle capacity and quality [11]. When evaluating the effect of qualitative property after 10 weeks in our study, the NMES training program of 3 times per week resulted in a significant decrease in the muscle density and white area index.

These findings suggest that increase of muscle contraction force were associated with significant changes in skeletal muscle architecture and qualitative properties. Future studies may focus on a comparative study between qualitative and mechanical properties such as fascicle length, muscle volume and thickness.

5. CONCLUSION

Our findings indicate that NMES training of 50% MVIC, comparative low level, had influence on improvement of skeletal muscle architecture and qualitative properties, as well as muscle contraction force. In addition, to estimate the change of muscle, it may be preferable to measure the muscle architecture and qualitative properties.

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