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Effects of Electrostimulation with Blood Flow Restriction on Muscle Thickness and Strength of the Soleus

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ABSTRACT

Andrade SF, Skiba GH, Krueger E, Rodacki, AF. Effects of Electrostimulation with Blood Flow Restriction on Muscle Thickness and Strength of the Soleus. **JEPonline** 2016;19(3):59-69. The purpose of this study was to investigate the effects of low-intensity neuromuscular electrical stimulation (NMES) combined with blood flow restriction (BFR) to increase soleus muscle size and strength. Seven untrained males (22.5 ± 1.9 yrs) had one leg unilaterally trained with percutaneous NMES with BFR at 20% of their maximal capacity, 3 times·wk^{-1} for 6 wks, while the contralateral leg served as control (not trained). Soleus muscle thickness and isometric strength were measured before and after the training period. No changes were observed in both legs for soleus thickness and strength measurements. This study showed that low-intensity NMES training combined with BFR does not induce increases in strength and size in the soleus.

Key Words: Blood Flow Restriction, Electrical Stimulation, Soleus, Muscle Thickness

INTRODUCTION

The application of voluntary training with very low loads (10 to 30% of 1RM) combined with moderate blood flow restriction (BFR) has been demonstrated to elicit substantial hypertrophy and strength in the lower limb muscles (1,5,29,35). This method has been regarded as an important strategy to prevent atrophy following surgery and/or to counteract pathological conditions associated with muscle wasting, such as rheumatoid arthritis and neurological disorders (9). Although the underlying mechanisms remain undefined, recent studies have suggested that the acute muscle cell swelling induced by blood pooling and accumulation of metabolites may stimulate the positive net protein balance (25,53). Furthermore, it is likely that other mechanisms may also play a role and include decreased myostatin (21), augmented activation of satellite cells (34), and increased fiber type recruitment (27). Research indicates that the main advantage of BFR training is the use of relatively low loads, which prevents high mechanical stress placed on the joints and exercise-induced muscle damage (23).

There are a number of conditions in which even low-force voluntary contractions may not constitute the suitable stimulus. In these cases, traditional neuromuscular electrical stimulation (NMES) is commonly used in clinical settings to emulate voluntary contractions (14). Most studies have investigated the effects of NMES at near maximal intensities (relative to pain tolerance) since intensities bellow the pain threshold are unable cause large motor unit recruitment (31). Lower and more tolerable intensities may be ineffective to provide a training stimulus with traditional NMES protocols (19).

Thus, the combination of NMES and BFR seems attractive in promoting muscle strength and size. This has been recently demonstrated by Natsume and colleagues (33) in the quadriceps femoris. However, given the predominance of type II fast twitch fibers in the quadriceps, it is possible that NMES training with BFR might constitute an effective stimulus to some specific muscles. It has been demonstrated that fast twitch fibers respond more to BFR than slow twitch fibers (28). However, it is not known whether NMES combined with BFR training will result in an muscle strength and hypertrophy of muscles are predominantly formed by slow twitch muscle fibers (such as the soleus). In this study, it has been hypothesized that the soleus muscle will show no significant changes in strength and hypertrophy in response to NMES and BFR training.

METHODS

Subjects

Seven untrained young male volunteers (age: 22.5 ± 1.9 yrs; body weight: 73.2 ± 9.4 kg; height: 1.74 ± 0.11 m) participated in the study. The exclusion criteria were: (a) participate in regular resistance training during the last 24 months; and (b) recent knee and ankle injury or surgery and cardiovascular diseases (e.g., thrombosis, hypertension). All subjects were informed of the methods, procedures, and risks involved in the experiment, and each subject signed an informed consent form that was approved by the local Institutional Review Board in accordance with the Helsinki Declaration of 1975, as revised in 1983.

Procedures
Strength Assessment
The unilateral isometric strength assessments were conducted in a seated heel-raise machine specially adapted for this study. The subjects were comfortably seated with the knee positioned at 90º and the ankle in a neutral position. The distal end of the thigh was firmly stabilized under the machine cushion pad. The tested limb had the forefoot supported on a 4 cm rigid block, while the other limb had the foot comfortably supported on the floor. This position allowed the soleus plantar flexion strength to be measured statically, with the gastrocnemius muscles in active insufficiency (42). The force was measured with a load cell (EMG Systems™, São Paulo, Brazil) attached under the machine's lever arm. Three trials of 5-sec maximal voluntary isometric contractions were performed. Verbal encouragement was provided and an interval of 120 sec was imposed between each trial for trained and control legs. The highest peak force among trials was used for further analysis.

Ultrasound Measurement
Subjects were asked to lie in a prone position while resting comfortably with their feet freely hanging over the table edge. The soleus muscle thickness (MT) was measured with a real-time B-mode ultrasonography using a linear array 11-MHz ultra-sound probe (Logiq Book XP, General Electric™, USA) positioned perpendicularly to the calcaneous tendon 2 cm below the medial and lateral gastrocnemius bellies. A hypo-echoic tape was placed on the skin as a shadowing reference in the obtained image. In order to ensure minimal pressure on the skin and adequate sound coupling, a water-soluble transmission gel was placed over the scanned head. A built-in software cursor was then used to measure the soleus muscle thickness, defined as the anterior-posterior distance between the anterior and posterior parallel fasciae of the soleus, according to the procedures reported in the study of Fujiwara et al. (8). Post-training measurements were conducted at least 48 hrs apart from the last training session in order to avoid the measure of a possible residual edema.

Training Protocol
Subjects trained 3 $d \cdot wk^{-1}$ for 6 wks. Training was performed in the same seated heel raise machine used for the isometric strength tests with a load cell attached to the machine lever arm. During the sessions, the subjects were instructed to relax their calf muscles as much as possible. In order to control the training intensity, a computer monitored in real-time the force produced during each contraction.

The soleus was stimulated using bipolar flexible silicon electrodes linked to a neuromuscular electrical stimulator (model Dualpex 961, Quark™, Brazil). The negative electrode (9 x 5 cm) was placed proximally about 2 cm below the popliteal fossa, whereas the positive electrode was placed just below the lateral and medial gastrocnemius belly. Both electrodes were positioned transversally to the leg longitudinal axis. The stimulator discharged biphasic rectangular pulses at a frequency of 35 Hz and 400 μs of pulse width. The electrical stimulator was programmed to deliver ramped duty cycles with 6-sec of sustained contractions and 2-sec of ascent/descent phases with no pause. The current amplitude was set at 20% of the maximal voluntary isometric contraction (MVIC). The NMES was interrupted when decrements in the force output (fatigue) reached approximately 10% of the MVIC. Three sets of NMES were performed with 1-min rest between each. The control leg was not stimulated.

The blood flow was partially restricted with an air cuff placed immediately below the inguinal fold (250 mm width x 900 mm length). The cuff placed on the thigh was inflated up to 100 mmHg pressure, which was sustained throughout the training session (that included the rest intervals). This pressure has been showed elsewhere (26) to sufficiently restrict the venous return without excessive pain or discomfort.

Statistical Analyses

All results are expressed as means ± standard deviations. Nonparametric statistics were conducted for pre-training and post-training muscle thickness (MT) and isometric strength measurements (ISOM). The Wilcoxon signed rank was used to test for dependent paired samples, with the significance level set as P<0.05. All statistical procedures were calculated using the SPSS statistical software package (IBM, USA, version 19.0).

RESULTS

Table 1. Mean and Standard Deviations for Thickness and Strength Measurements.

	Muscle Thickness				Isometric Strength			
	Pre	Post	P	ES	Pre	Post	P	ES
Trained	14.4 ± 3.5	16.6 ± 4.9	0.091	0.5	103.4 ± 12.1	108.6 ± 17.4	0.208	0.4
Control	15.5 ± 4.1	15.1 ± 4.0	0.141	0.1	88.4 ± 23.6	95.1 ± 20.7	0.139	0.3

All muscle thickness (MT) measurements are in millimeters. ES = effect size. Strength measurements are in Kgf. Statistical significance was set at P<0.05

DISCUSSION

In the present study, NMES was applied to induce low-force isometric contractions while the muscle venous return was partially restricted through a controlled external pressure. To the best of our knowledge, this was the first study to investigate the effects of a passive training with BFR on the morphology and isometric strength of primarily slow-twitch muscle fibers. The main finding of this study was that the combination of low-intensity NMES training with BFR had no effect on the soleus muscle thickness and maximal isometric voluntary contraction.

These findings are in disagreement with those reported by Natsume and colleagues (33), who showed increases in muscle thickness of the quadriceps after 2 wks of NMES and BFR exercises. Differences in training time (twice daily, 5 $d \cdot wk^{-1}$) made it difficult for further comparisons between studies. A lower training frequency was selected because a recent meta-analysis demonstrated that significant changes in strength and hypertrophy occur when BFR training was performed 2 to 3 $d \cdot wk^{-1}$, when compared to training 4 to 5 $d \cdot wk^{-1}$ (29). However, the total number of training sessions was quite similar, taking into account the longer duration of the present study (6 wks; 18 sessions) in comparison to Natsume and colleagues' work (2 wks; 20 sessions). Thus, the conflicting results between both studies cannot be attributed to the total training volume. Other training variables, such as the BFR duration, cuff pressure, NMES parameters, and muscle characteristics, may have played a role, but quantifying their individual contribution is not possible in order to explain the lack of changes in the present study.

Studies are conflicting with respect to the optimal duration of the BFR to promote morphological and functional adaptations in skeletal muscle. In this study, the BFR was sustained for ~10 $min \cdot session^{-1}$, which is comparable to the duration applied in previous studies that were successful in demonstrating positive changes in hypertrophy (1,36,41,53). Since the muscle reperfusion after the BFR is related to the duration of the occlusion (17), it might be possible that the soleus muscle requires longer periods to elicit a hypertrophic effect. Recent studies have demonstrated that the acute reactive hyperemia induced by the reperfusion after the BFR cessation can be regarded as one of the potential mechanisms to hypertrophy (15,25). The water flow from the blood stream into the muscle cells relies highly on a family of water channel proteins called aquaporins (51). Specifically, aquaporin-4 (AQP4) is the major water channel of the skeletal muscle cells, and it is primarily found in fast-twitch muscle fibers (7).

Previous BFR training studies (20-22) have demonstrated significant muscle hypertrophy with cuff pressures similar to the pressure applied in this study (~100 mmHg). For example, Natsume et al. (33) applied 140 mmHg during NMES with BFR on the quadriceps and reported significant increases in muscle thickness. There is no evidence to assume that a higher cuff pressure would be necessary to induce an anabolic stimulus in the soleus. Compelling evidence has shown that the cuff width has an impact on the pressure needed to cause blood flow restriction (3,47). In this regard, a relatively wide cuff (240 mm) was used to cover most of the thigh length. The cuff was assumed to be sufficient to cause blood flow occlusion. Nevertheless, previous research indicates that muscle contractions facilitate venous return, thereby compensating for the BFR condition (30). Thus, it seems plausible that the intermittent contractions of the calf muscles may have prevented severe metabolite accumulation.

The duration of each training session varied according to the time required to induce force decrements caused by the soleus fatigue, after several sustained isometric contractions. In this study, the chosen duration of the train pulse (6 sec) was based on the concept of time under tension. According to this concept, it is believed that prolonged bouts of sustained contractions lead to greater metabolites (lactate, H^+, P_i) build-up (28). In BFR training, the application of an external pressure causes an acute venous blood pooling that induces metabolite accumulation, which has been proposed as a stimulus for the augmented muscle protein synthesis (27). Furthermore, the increase in the intramuscular metabolites has been associated with an increase in acute serum growth hormone levels (38). For example, BFR training has been showed to elicit an increase as high as 290-fold baseline levels (48). However, it should be noted that the role of acute increases of anabolic hormones to stimulate hypertrophy has been recently questioned (52). On the other hand, if it was assumed that acute increases of anabolic hormones are a driving factor to hypertrophy, it could be argued that the soleus is too small to elicit expressive metabolites accumulation from NMES with BFR training. It is well documented that exercises that involve large muscle groups (e.g., quadriceps) promote higher acute hormonal responses (18).

Another mechanism to explain the effects of low-intensity BFR training on muscle hypertrophy is the increased motor unit recruitment, especially in motor units that innervate larger muscle fibers (39). According to this hypothesis, it is believed that the fatigue onset occurs earlier with the application of BFR, thereby recruiting primarily the larger type II fibers despite the low training intensities (24). Thus, BFR training seems to cause a reversion of the so-called size principle, which dictates that in voluntary contractions the motor units are orderly recruited from the smallest to the larger ones until all available fibers are activated (16). However, during NMES training, the muscle contractions are evoked through the transcutaneous stimulation of the motor nerve, which leads to a non-selective, synchronic activation of fiber types I and II (12,13).

In the present study, it is possible that even though the larger fibers were synchronically recruited, the frequency selected for the electrical stimulation (35 Hz) was not sufficient to elicit fatigue of the soleus muscle. Indeed, a number of studies have consistently reported that higher frequencies are associated to higher increases in inorganic phosphate and H^+, which are both showed to cause muscle fatigue (6,11,40). For instance, Gorgey et al. (11) demonstrated that decreasing the stimulation frequency from 100 to 25 Hz resulted in a decreased fatigue from 76% to 39%, respectively. Moreover, high stimulation frequencies (above 75 Hz, for instance) caused impaired motor nerve conduction due to an increase in K^+ in the extracellular fluid (2). Lower frequencies were chosen because control trials showed that the combination of BFR with higher frequencies resulted in a rapid fatigue onset and thereby a shorter time under tension. It should be also noted that isometric contractions have a high metabolic cost (40) in comparison to other contractions. Therefore, additional work is required to determine whether isometric contractions longer than the 6-sec are necessary to provide a sufficient metabolic stress to the soleus hypertrophy.

Although the soleus is a deep muscle, its innervation through the tibial nerve is superficial and can be easily stimulated due to the low subcutaneous impedance (44,45). Thus, it was assumed that even the relatively low-intensity electrical current was sufficient to stimulate most motor units supplied by this nerve. However, the soleus is comprised primarily of slow-twitch fibers (80 to 100%), which have lower hypertrophic potential in comparison to type II fibers (50). In addition, the soleus is highly resistant to fatigue due to its constant tonic activity in standing posture control (4). This is in line with previous observations that suggest that the soleus is a low responsive muscle to both voluntary (49,50) and passive training (32). Thus, it is likely that the combined training protocol (NMES plus BFR) may have been insufficient to activate the anabolic pathways in this muscle.

Surprisingly, no increase was found in the soleus isometric strength. It was expected that strength gains would occur based on previous investigations that reported MVC increases with submaximal NMES training intensities (10). These conflicting findings may reinforce the suggestion that the soleus are inherently low responsive to strength training, when compared to fast muscles (e.g., vastus lateralis) (50). This might be especially true taking into account previous studies that demonstrated strength gains in the quadriceps with NMES at training intensities as low as 5% of the pre-test MVC (46). Other investigators suggest that higher NMES training intensities are necessary to produce higher strength gains (19). However, the application of a high electrical current amplitude activates nociceptors, which inevitably leads to pain and, consequently, thereby making NMES an uncomfortable technique.

This study has some limitations. From the twelve enrolled participants, only seven managed to follow the 3-d·wk^{-1} training frequency throughout the 6 wks of the experiment. Two training sessions missed consecutively required exclusion from the study. In addition, all subjects were physical education graduate students. Although they reported to have not being enrolled in any other kind of training, their levels of regular physical activity might require a more fatiguing NMES stimulation protocol to elicit an adaptation. Thus, we cannot state with certainty that the absence of an effect on the soleus thickness and isometric strength was due to our sample size. However, a recent review has showed that even athletes can benefit from voluntary low-intensity BFR training (43). More studies with other NMES parameters are warranted in order to verify the possibility of a completely passive training with BFR to promote increases in muscle thickness and/or strength.

CONCLUSIONS

This study showed that the combination of low-intensity NMES training with BFR did not promote an increase in the size and strength of the soleus. Other parameters of NMES, such as higher pulse frequencies and longer sustained isometric contractions, should be investigated in order to verify the efficacy of this technique in promoting hypertrophy in the soleus and/or to prevent the atrophy caused by immobilization periods.

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