Electrically stimulating antagonist muscles could improve strength in older men: A pilot study

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Y. Takano, H. Matsuse, Y. Haneda, Y. Tsukada, N. Shiba, Y. Tagawa, Electrically stimulating antagonist muscles could improve strength in older men: A pilot study. Gerontechnology 2015;13(4):420-425; doi:10.4017/gt.2015.13.4.006.00 **Aim** The purpose of this study is to investigate the feasibility of the newly developed exercise method with neuromuscular electrical stimulation on muscle strength and physical activities in healthy older men. **Methodology** Six subjects performed a 15min cycling exercise twice a week for 6 weeks. Electrical stimulation was applied to both the gluteus maximus and hamstrings. Before and after the 6-week training period the following parameters were measured: (i) maximal isokinetic torque of hip-flexors (HF) and hip-extensors (HE), knee-flexors (KF) and knee-extensors (KE), (ii) 10m maximal gait speed, (iii) chair-stand test-5 times, (iv) stair climbing (10 stairs of 0.2m height at maximal speed), and (v) 6min walking. None of the subjects had any injuries during the study period. **Results** Maximal isokinetic torques improved (KF: 51%; KE: 25%), as well as other physical parameters (10m gait speed: 22%; chair-stand test: 22%; stair climbing: 19%). **Conclusion** We conclude that electrically stimulating antagonist muscles during cycling training has the potential to become a safe, effective method of muscle exercise for healthy older men.

Keywords: electrical stimulation, ergometer exercise, cycling, older men

Neuromuscular electrical stimulation (NMES) is an exercise method that improves muscle strength and physical activities in patients with immobilization-associated muscle atrophy or with difficulty in making voluntary motions[1,2]. It also increases muscle strength and muscle mass in healthy subjects[3]. A combination of electrically stimulated muscle contraction (ESMC) and voluntary muscle contraction (VMC) is considered to be more effective than electrical stimulation (ES) or VMC alone[4,5]. Ambrosini et al.[6] reported that cycling with functional electrical stimulation training improved lower extremity motor function and accelerated the recovery of over-ground locomotion. Cycling exercise with ES has been shown to be beneficial in patients with stroke[7,8] and orthopedic disease[9] in rehabilitation medicine.

Cycling exercise is widely used in rehabilitation centers. It not only improves muscle strength, but also expands range of motion of lower extremities without excessive strain on the knee-joint[10,11]. In addition, cycling exercise has also been reported to help improve endurance and physical fitness[12,13]. However, its effects on muscle strength have not been demonstrated under aerobic circumstances[14,15].

We developed a cycling exercise based on an ES program that combines ESMC and VMC. It creates resistance to the motion of the voluntary muscle that contracts against the electrically-stimulated antagonist muscle. The aim of this study is to demonstrate the feasibility of this exercise method to increase muscle strength and gait speed.

Methodology

Participants

The protocol of the study was approved by the Ethics Committee of Kurume University. The subjects were recruited by posters displayed in local community centers in Omuta City, Fukuoka, Japan. The exclusion criteria from the intervention included cerebrovascular or heart disease in the past one year, as well as acute problems, such as pain in the legs and osteoarthritis of the knee and hip joints, and dementia. Informed consent to participate in the study was obtained from a convenience sample of six healthy older men (mean age 72.5±5.9 years; height 159.7±4.8 cm; weight 59.3±6.6 kg). None of the subjects had performed regular resistance exercise.

Cycling exercise system

The cycling exercise system consisted of a recumbent ergometer, an electrostimulator, a personal computer (PC), and a chair. By using the incremented rotary encoder installed in the rotation axis of the ergometer, angular information from the crank was measured. Then the information was sent to the PC through a cable. Subsequently, the ES commands set on the PC were delivered to the body to gain muscular contraction. The ankle-joints of both legs were fixed with short plastic leg braces. Motion of the hip- and knee-joint was not constrained, and the position between the chair and the ergometer was adjusted so that the subjects could exert their maximal strength. The ergometer did not involve any external powered instruments.

The target muscles in this study were gluteus maximus (GM) and the hamstring (HAM); each muscle was stimulated through 2 channels: 4 channels in both legs. Information on the crank angle was loaded on to the PC in which the ES program had been installed. Based on the obtained information, the ES pattern and value were determined. For the operation procedure, data on the subject's height, the chair height, and the distance between the ergometer and the chair were put into the PC. The ES interval was decided according to the information on the crank angle. On the PC screen, a human cycling model of the subject was generated based on the body-height information. With the motion of the subject and the human cycling model synchronized, the motion was observed by the subject himself.

The target cycling speed was approximately 60 rotations/min, which was not considered to affect blood pressure or heart rate[17]. The subject was able to observe and maintain the cycling speed in real time on the PC screen. As changes from the target speed time were displayed on the PC screen, the subject was able to provide self-adjustment. The voltage of each channel was shown on the PC screen. The output variable value 'elapsed time of the exercise' was used to adjust ES intensity.

Electrical stimulation

The ES waveform used in the ergometer exercise was a bi-phase voltage square wave with a maximal peak-to-peak voltage of 80V (carrier frequency: 5kHz; stimulus duration: 2.4ms, stimulation frequency 40Hz). ES intensity in the exercise evaluation was 80% of the maximal tolerable voltage, as taken from previous studies[19,20]. ES intensity was set twice: before the start of the study and 3 weeks after. Surface electrodes (a conductive gel adhered to copper foil, 40mm×120mm for GM, 90mm×90mm for HAM), were placed over each motor point with a detector (*Figure 1*). The size of the electrode selected achieved the maximal enlargement of the subject's muscle. In order to cover large GM, a horizontally spread electrode was used, and a vertically spread electrode for HAM. To prevent the deterioration of electrode impedance, the electrode was replaced once every 3 uses.

Figure 1. Surface electrodes as placed over motor points of each muscle (size); GH=Gluteus maximus (Electrodes: 40mm×120mm); HAM=Hamstrings (Electrodes:90mm×90mm)

The pattern on which ES started and stopped by the system was steered by the crank angle (0-360°) in one cycle of the ergometer. The crank angle produced by a subject at a particular moment is calculated from the knee angle. The program starts ES of a particular muscle at a prescribed crank angle and stops it at another prescribed angle. Consequently, ES is provided for all subjects on the same pattern (*Figure 2)*.

Crank angle, θ (°), the length of crank, l_c (m), height of crank, h_e (m), crank angle (encoder information), body height, and height of the chair, h_c (m), and distance between the chair and the

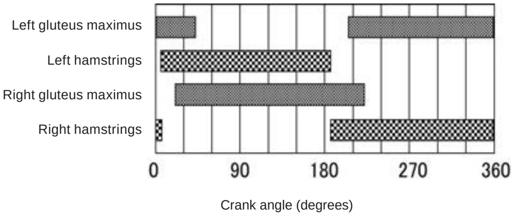

Figure 2. Electrical stimulation pattern by the system as generated by the computer program based on the joint angles

ergometer, w (m), were entered into the PC (*Figure 3*). Information on the length of the thighs, l_d (m), and lower legs, l_k (m), was also necessary and derived from a percentage of body height[18]. The horizontal distance between the pedal and chair was defined as $w - l_c \cos\theta$ (m), and the vertical distance was defined as $h_c - h_e - l_c \sin\theta$ (m). Therefore, the linear distance between the pedal and the chair, l_{pc} (meter), was:

$$l_{pc} = \sqrt{(w - l_c\cos\theta)^2 + (h_c - h_e - l_c\sin\theta)^2} \quad [1]$$

Based on the cosine theory, the knee-joint angle, β (degrees), was defined as:

$$\beta = \cos^{-1}\left(\frac{l_d^{\,2} + l_k^{\,2} - l_p^{\,2}}{2 l_d l_k}\right) \quad [2]$$

The angle of the hip joint, α (degrees), was described as:

$$\alpha = 180 - \cos^{-1}\left(\frac{l_d^{\,2} + l_{pc}^{\,2} - l_k^{\,2}}{2 l_d l_{pc}}\right) - \cos^{-1}\left(\frac{h_c - h_e - l_c\sin\theta}{l_{pc}}\right) \quad [3]$$

Exercise protocol

All exercises were performed at the university laboratory. The exercise was 19min long per session, and it was taken twice a week for 6 weeks (a total of 12 sessions). Sessions were separated by an interval of at least 48hrs. Subjects were instructed to avoid excessive exercise during the intervention period and to carry on their ordinary daily living. During the exercise, an assistant was always present to provide guidance and monitoring in order to ensure that the exercise could be performed safely and properly. The pulse rate and blood pressure of the subjects were measured by the automatic sphygmomanometer before and after the exercise at each session.

Measurements

All the measurements were performed with a blinded evaluator, who was not aware of it being a week before or a week after the exercise.

Muscle strength. The Biodex System3-PRO (Biodex Medical Systems Inc., Shirely, NY, USA) was used for measuring the maximal isokinetic torques of HF, HE, KF and KE of the non-dominant leg as a 60°-speed concentric isokinetic strength from knee flexion (90°) to full extension (0°). The subject's seat was kept in the same position at each measurement. HF and HE muscle strength measuring was performed in an upright position from hip extension (0°) to full flexion (90°), and pre-exercise was done to prevent compensatory motions. In addition, the evaluator manually fixed the subject from behind to prevent the elevation of their iliac bone. In both measurements, the 3s flexion-extension was performed 3 times/session for 2 sessions. In these 2 sessions, the maximal isokinetic torque divided by the body weight (Nm/kg) was calculated. The session with the highest value was used for analysis.

10m maximal gait speed. In the 10m maximal gait speed, 2m were added to allow for acceleration before, and deceleration after. The subjects were instructed to walk as fast as possible. Evaluations by two evaluators were averaged.

Chair-stand test-5times. A 0.4m high chair with a backrest was used; the subject's legs were spread, and their hands were placed in front of the chest. From a sitting position, the subjects were instructed to stand up 5 times at maximal pace. Evaluations by two evaluators were averaged.

Stair-climbing. The subjects were instructed to climb 10 stairs of 0.2m height on their own at maximal speed. The time it took to climb the stairs was measured. Evaluations by two evaluators were averaged.

6min-walking test. In a 25-meter oval walking course at an indoor sport center, subjects

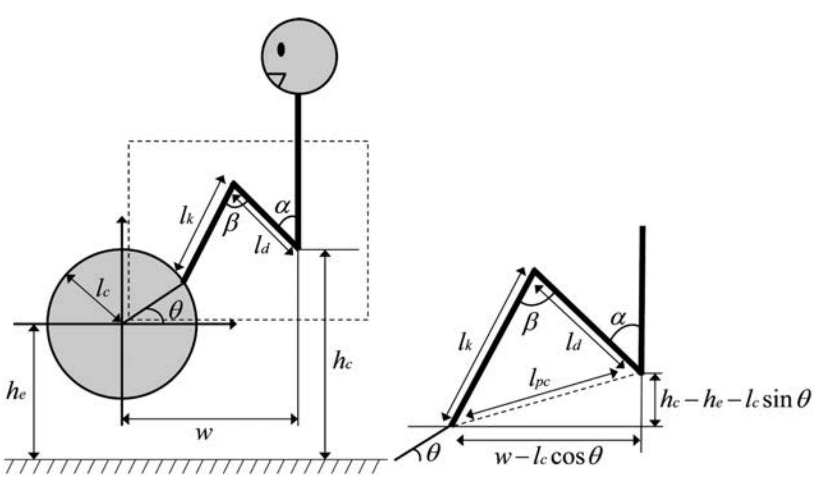

Figure 3. Experimental set-up; left (A): hip-joint angle (α), right (B): knee joint angle (β); θ = crank degrees; l_c = length of crank, m; h_e = distance between the center of crank and the floor, m; h_c = distance between the chair and the floor, m; w = distance between the chair and the ergometer, m; l_d = length of the thigh, m; l_k = length of the leg, m; l_{pc} = distance between pedal and chair

walked at a regular walking speed for 6min, and their walking distances were measured. Before the test, the subjects rested for 30min, and their blood pressure and pulse were taken. The evaluation was suspended if the subjects were unable to walk or did not feel well.

Statistical Analyses

Statistical analyses were performed by the SPSS ver14.0J (SPSS Japan Inc., Tokyo, Japan) at a confidence level of 0.05. All data were expressed as median (interquartile range). A Wilcoxon signed rank test was used to compare test data before and after the exercise.

Results

No subjects withdrew from this exercise, and they all successfully completed their 2x/week cycling exercise program of 6-weeks duration. No subjects complained of discomfort or pain. Further results are shown in *Table 1*.

The maximal isokinetic torques of KF (+51%, p=0.028) and KE (+25%, p=0.028) significantly increased from the pre-exercise to the post-exercise. The rate of increase in HF (p=0.116) and HE (p=0.075) was not significant.

The 10-meter maximal gait speed (+22%, p=0.028), the chair-stand test-5 times (+22%, p=0.028) and the stair-climbing (+19%, p=0.028) showed a significant improvement from the pre-exercise to the post-exercise period; however, the 6-minute walking test did not (p=0.075).

Discussion

The primary objective of our study was to evaluate the feasibility of using a cycling exercise system, which combined ESMC and VMC, to improve muscle strength and physical activities in healthy older men.

Muscle strength

Westing et al.[21] reported that the eccentric muscle contraction generated 30% to 50% more muscle strength than concentric muscle contraction, and 15% to 25% more than isometric contraction. Mackenzie et al.[16] reported that electrically stimulated eccentric antagonist contractions can increase the muscle strength of not only the antagonist, but also the agonist. This fact suggests that the eccentric muscle contraction significantly increased muscle strength. Lastayo et al.[22] reported a 36% improvement of KE muscle strength by using the eccentric cycling exercise in healthy young subjects. The characteristic of this method lies in co-contraction via agonist and antagonist muscles created by the combined ESMC and VMC. Recent studies have reported effects of the combined ESMC and VMC on improving muscle strength[12]. According to Henneman's size principle[26], VMC depends on motor load, and fibers are activated in the order of type I to type II fibers. However, NMES does not activate fibers in the same order; therefore, muscle contraction is promoted by type II fibers[24]. Therefore, the muscle contraction of type I fiber in VMC and of type II fiber on ES might have occurred alternately in this study. Furthermore, this cycling exercise is advantageous since it provides not only a simple cycling exercise on the conventional ergometer, but also exercise based on co-contraction by using the combined ESMC and VMC, which improves physical activities in older men. On the other hand, no significant changes in HE muscle strength occurred. During the cycling exercise, leg lifting needs HF muscle strength. One reason why no significant effect was found in this study could have been due to insufficient ES on GM. Similarly, having no significant effect on eccentric-ESMC of HAM could have been due to low-activation caused by the narrow hip-joint angle during the cycling full cycle, which might have led to insufficient motor load.

Table 1. Muscle strength and physical activities before and after a 6-weeks cycling program with electrical antagonist stimulation; confidence limit=0.05; significant values in the Wilcoxon sign rank test in bold

Parameter	Pre-test		Post test		p
	Mean±SD	**Interquartile range**	**Mean±SD**	**Interquartile range**	
Muscle strength, Nm					
Hip flexors	85.5±23.4	48.1-116.3	90.7±23.2	72.7-131.2	0.116
Hip extensors	118.9±49.2	72.0-180.2	137.7±38.6	87.9-195.7	0.075
Knee flexors	58.4±29.1	23.8-90.7	88.1±25.7	55.2-109.7	**0.028**
Knee extensors	117.9±50.0	69.9-192.9	147.3±55.3	86.1-231.4	**0.028**
Physical activities					
10m maximal gait speed, s/10m	7.4±0.7	6.5-8.6	5.8±0.6	5.4-6.8	**0.028**
Chair-stand 5 times, s	5.9±0.6	5.2-6.7	4.6±0.5	3.8-5.1	**0.028**
Stair climbing, s	7.4±0.8	6.5-8.5	6.0±1.5	4.3-8.3	**0.028**
6min walking, m	510.7± 54.9	473-607	520.8±45.0	478-579	0.075

Physical activity

Cycling exercises differ from knee flexion-extension exercises in the typical sitting position since feet work on the pedal creates the factor of a closed kinetic chain, which contracts the agonist and antagonist muscles of the lower extremity. In addition, co-contraction via ESMC and VMC may also increase the factor of closed kinetic chain. Exercise programs using co-contraction stabilize the stance phase of walking, enabling a larger swing phase, and improving walking speed[19]. Exercise with co-contraction via KE and KF is considered especially beneficial for improving physical activities in older men. This co-contraction improves a static balance for all physical activities. Cycling exercise is said to activate the medial and lateral vastus muscles[4,25]. It also improves the stability of muscles in the knee and the lower extremities. In this study, an improvement trend of the subjects' muscle strength in stair-climbing was also found. It could be that compared to the leg extension in a sitting position by using a weight machine, cycling exercise enhances the mobility of hip- and knee-joint muscle, which helps to ease stair-climbing. These results suggest that cycling strengthens eccentric muscle contraction required to stand up from the chair and climbing stairs.

The 6-minute walking test is correlated with daily life activities, and walking distance diminishes with age.[26] We found no significant effect of the cycling intervention on the 6-minute walking test.

Limitations

The small sample size and the absence of a control group undergoing exercise without ESMC limit our study. In addition, the study did not measure motor load, making it difficult to confirm an improvement in muscle strength and power. But as a pilot investigation it has demonstrated the feasibility and potential for improving muscle strength and power.

Conclusion

Cycling exercise is known to increase a maximal oxygen uptake[27] as pedaling increases energy consumption. This study suggested that the exercise method combining cycling and ES could enhance the ability of exercise tolerance.

The cycling exercise method, which combined ESMC and VMC, showed potential for improving muscle strength and physical activity. Although the sample size was limited, all the subjects completed all of the tests. The novel ergometer employed for the exercise method is advantageous compared to the conventional ergometer.

Acknowledgment

This study was supported in part by the Japanese Society for the Promotion of Science (20500469, 20360118)

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