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Original Article

Superimposed electromyostimulation of the thigh muscles during passive isokinetic cycling increases muscle strength without effort

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Abstract

Objectives: This study was designed to investigate the effects of a completely passive isokinetic cycle (PIC) exercise with electromyostimulation (EMS) on improving muscle strength and the changes in kinesthesia during daily activities. **Methods**: Twenty-nine sedentary females were divided into three groups. The EMS anterior and whole groups performed the PIC exercise without EMS 3 times a week for 3 weeks, followed by a 1-week break, and then performed it with EMS applied to the anterior and entire thigh muscles, respectively, 3 times a week for 3 weeks. The control group did not perform any training. **Results**: The PIC exercise with EMS significantly increased the 30s chair stand test scores by 12-16% and the maximum isometric knee extension and flexion torques by 38-68% in both EMS-applied groups. The participants found its exercise easy and felt more comfortable with daily physical activities. The exercise without EMS did not show similar improvements. Muscle soreness was significantly greater in the EMS anterior group than in the EMS whole group; however, it was not severe. **Conclusions**: The PIC exercise with EMS resulted in significant increases in muscle strength, facilitating a perceived ease of daily physical activities, while minimizing difficulties, effort, and notable muscle soreness.

Keywords: Electromyostimulation, Kinesthesia, Muscle Strength, Passive Isokinetic Cycle Exercise, Sarcopenia Prevention

Introduction

Sarcopenia is a common muscle disease in the elderly rooted in adverse muscle changes that accrue across a lifetime and is defined by low levels of measures for three parameters as an indicator of severity: (1) muscle strength, (2) muscle quantity and quality, and (3) physical performance[1]. Sarcopenia is common in the elderly but has been suggested to be influenced by the early environment and subsequent development[2], indicating that it is a muscle disease with many causes beyond aging across a lifetime[1]. A major risk factor for sarcopenia is age, muscular anabolic resistance, lipotoxicity, inflammation[3], and a decrease in physical activity or immobility with a marked decrease in the number of muscle fibers and muscle strength[4], which is particularly related to atrophy and loss of fast-twitch motor units[5].

Sarcopenia is also a major component of frailty[6], which is defined as a medical syndrome with multiple causes and contributors. Frailty is characterized by diminished strength, endurance, and reduced physiologic function, which increases an individual's vulnerability for developing increased dependency and/or death[7]. A systematic review on the prevalence of sarcopenia reported an overall prevalence of 10%[8,9], using the EWGSOP2 definition[1]. Meanwhile, a separate review on frailty prevalence revealed a prevalence of 12% in individuals aged 50 years and older[10]. However, the prevalence of pre-sarcopenia and pre-frailty, recognized as prodromal states before the onset of clinically identifiable

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sarcopenia and frailty, increases by 22-30%[11] and 46%[10], respectively. This indicates the need to take action before the onset of these conditions. Disuse muscle atrophy, which occurs in the musculoskeletal system due to inactivity and bed rest, also leads to a reduction in muscle strength and mass through mechanisms that differ from those of sarcopenia[12]. These mechanisms include no change in the number of muscle fibers, atrophy and loss of slow motor units, and rapid progressive loss of muscle strength within a short period of time.

Regular exercise training, including resistance and endurance exercises, has a beneficial effect on preventing the progression of sarcopenia, frailty[13-16], and disuse muscle atrophy[17], despite their differing developmental processes. Furthermore, multimodal combinations of resistance and endurance exercise training can more effectively improve muscle mass, strength, and function[18]. These findings suggest that the most fundamental approach to avoiding the risk of these diseases is to end sedentary or immobile lifestyle and adopt an active lifestyle and exercise routine. Particularly, maintaining muscle mass, strength, and function in the thighs, which play a major role in performing daily activities, is essential for maintaining a high quality of life. However, more than a quarter of the world's adult population has been reported to be insufficiently physically active, although there are differences in the levels of activity according to region, income, and sex[19]. In older people, the decline in regular exercise routines is even greater, despite the increased risk of sarcopenia with aging[20]. High-intensity and power training have been reported to be effective in improving muscle mass and strength in older individuals[21]. However, undertaking such activities may prove challenging for them.

Having limited time, lack of knowledge, inadequate fitness level, and the physical challenges associated with exercise (e.g., too physically demanding, painful, dangerous) are common reasons for people of all ages to not engaging in physical activity[22]. However, overcoming these barriers can be significantly challenging for individuals in inadequate environments for voluntary exercise or who are not good at performing exercises. Autonomous motivation plays a crucial role in promoting changes in health behavior. This motivation can be enhanced by engaging in manageable physical activity without straining and developing a sense of competence[23]. Therefore, engaging in physical activity that avoids these barriers rather than overcoming them, improving physical fitness, and increasing the perceived competence in exercise can serve as an effective initial step towards establishing an active exercise routine in daily life.

The combination of isokinetic, passive, and easy exercises with electromyostimulation (EMS) may offer an effective exercise approach that possesses several advantages: 1) it does not require physical effort or strength, 2) it is easy to perform, 3) it carries a low risk of injury, and 4) it can be performed while engaging in other activities. This is because EMS involves more synchronized[24], passive muscle fiber contraction, nonselective muscle fiber recruitment even at low exercise intensities[25], and stimulation and activation of the central nervous system[26]. Additionally, isokinetic exercises are characterized by not causing instantaneous impact or excessive stretching of the muscle–tendon complex. Therefore, a completely passive isokinetic cycle (PIC) exercise while superimposing EMS on the thigh muscles may be a simple and safe exercise method for anyone to passively elicit lower limb movement while passively contracting the muscles, particularly fast-twitch muscle fibers even at low EMS intensity.

Previous studies have frequently combined EMS with voluntary exercise to prevent and improve diseases such as sarcopenia, frailty, and disuse muscle atrophy[27]. However, it is uncertain whether engaging in a completely passive exercise with EMS can effectively prevent diseases such as sarcopenia, frailty, and disuse muscle atrophy. Therefore, we hypothesized that PIC exercises with EMS will improve muscle strength effortlessly, reduce the strain of daily activities, and increase the likelihood of promoting vigorous voluntary movements. A previous study has reported that symptoms clinically identifiable as sarcopenia are observed in 15% to 20% of individuals in their 20s[28], and there is concern also in Japan about a decrease in skeletal muscle mass, particularly among young women[29]. This study aimed to test our hypotheses in female university students with sedentary lifestyles who do not engage in regular exercise and determine whether PIC exercises with EMS could serve as a means of preventing sarcopenia, frailty, and disuse muscle atrophy.

Materials and Methods

Trial design and participants

The investigation was designed as a three-arm parallel randomized controlled exercise trial with three different training groups: 1) EMS anterior, 2) EMS whole, and 3) control groups. Thirty sedentary female university students who do not exercise regularly participated in this study. However, one of them had suspected coronavirus disease 2019 during the training period and had to withdraw from the study for safety reasons. Exclusion criteria included previous experience with EMS training and the presence of a contraindication determined by doctors based on the results of medical examination. The EMS anterior group comprised nine participants who performed PIC exercises while EMS was applied to the anterior thigh muscles. The EMS whole group comprised 10 participants who performed PIC exercises while EMS was applied to the entire thigh muscles. The control group comprised 10 participants who did not perform any training during the training period. In the EMS-applied groups, it was not possible to blind the participants or the examiners to the application conditions of EMS. This was because the size of the electrodes used to apply EMS to the muscles differed between the two groups. Furthermore,

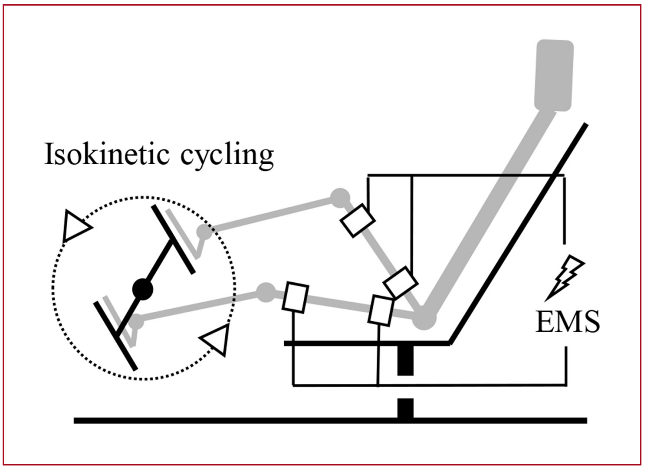

Figure 1. Completely passive isokinetic cycle (PIC) exercise with EMS applied to the thigh muscles.

the participants were able to perceive which muscles were being stimulated. However, all measurement outcomes were not communicated to the participants until the end of the experiment, and the examiners were only granted access to the measured values during the measurement phase.

PIC training with EMS

The EMS anterior and whole groups performed PIC exercises without EMS 3 times a week for 3 weeks (weeks 1–3), followed by a 1-week break, and then performed PIC exercises combined with EMS 3 times a week for 3 weeks (weeks 4–6). Both groups were asked to live their daily life normally, except for the training. The control group was also asked to continue life as usual throughout the 7-week training period.

PIC exercises were performed using an isokinetic cycle ergometer (Strength Ergo 240, Mitsubishi Electronics) (Figure 1). The participants sat on the ergometer in a position where their hip joints were aligned with the height of the axis of rotation of the pedals, the knee joint angle was 160° when the pedals were at their farthest position, and the hip joint angle was fixed at 120°, and their feet were fixed to the binding pedals. They were instructed to fully relax their muscles while pedaling. The PIC exercises were performed at 40 rpm for 10 min. According to the results of a preliminary experiment to familiarize the participants with the ergometer, 40 rpm was the revolution at which the participants were most comfortable performing the PIC exercises.

In the EMS anterior and whole groups, an exponential waveform of EMS with a frequency of 20 Hz (pulse width 260 μs) was applied to the anterior thigh and entire thigh muscles of both legs during the PIC exercises in weeks 4–6, respectively, using an EMS device (Elastic Pulse, Homer Ion). Belt electrodes with a horizontal length of the width of the target muscles and a vertical length of 6 cm were used. The electrodes were wetted with a moderate amount of water, and the anode and cathode were placed at the proximal and distal ends of the target muscles, respectively.

EMS intensity

EMS intensity was determined using an isokinetic dynamometer (Biodex System 4; Biodex Medical Systems) as follows: 1) the participant lay supine on the dynamometer chair with the center of the knee joint aligned with the rotation axis of the dynamometer and the knee joint flexed at 90°; 2) the shank was secured to the rotating arm with a soft cuff; 3) EMS was applied to the anterior thigh muscles while the participants fully relaxed their muscles; 4) the current value was gradually increased, and the value at which the isometric knee extension torque began to increase consistently was set as the initial EMS intensity. Such a posture was intended to reduce the slack of tendon tissue to make the condition of EMS-induced muscle contraction easier to detect[30]. The initial current values used for EMS were 2.56 ± 0.78 mA in the EMS anterior group and 2.39 ± 0.33 mA in the EMS whole group. The EMS intensity was set to the initial current value in week 4, which was increased by 10% in week 5 and by 20% in week 6.

Measurement and analysis of the training effects

The effects of training were evaluated before the start of the training period (Baseline), 3 days after the end of week 3 (Post 3W), and 3 days after the end of week 6 (Post 6W). The body mass and body fat percentage were measured using a body composition monitor (DC-430A; Tanita). The jump height or length in the counter movement jump (CMJ) and standing long jump (SLJ) were measured. The CMJ and SLJ were performed three times on a mat that automatically measures jump height (PH-1260; DKH) and on a gymnastic mat, respectively. All participants jumped with their hands on their waist to avoid the effects of arm swing. The score of the 30s chair stand test (CS-30)[31] was also measured once. Maximum isometric knee extension (MIKE) and flexion (MIKF) torque were measured three times using a dynamometer (Biodex System 4; Biodex Medical Systems) at knee joint angles of 20°, 45°, and 70° (maximum knee extension = 0°). The control group underwent the same tests as the EMS-applied groups at Baseline and Post 6W. The best record for each measurement was analyzed.

All participants were given a free-description questionnaire survey regarding the impact of training on the "ease of movement," which will be referred to as kinesthesia, in their daily physical activities at Post 3W and Post 6W. This included aspects such as the sensation of leg strength when ascending and descending stairs, walking, and cycling. The severity of muscle soreness was also investigated using a visual analog scale, where "none" and "severe"

Variable	EMS anterior	EMS whole	Control	p-value	η²
Age (yers)	21.0 ± 0.9	20.8 ± 0.9	20.4 ± 1.3	0.446	0.060
Height (m)	1.60 ± 0.05	1.55 ± 0.05	1.57 ± 0.04	0.126	0.148
Weight (kg)	52.9 ± 5.2	46.5 ± 6.2	48.1 ± 9.7	0.172	0.127
Body mass index (kg/m²)	20.8 ± 1.9	19.3 ± 2.5	19.4 ± 3.2	0.411	0.066
Body fat percentage (%)	26.5 ± 4.1	23.5 ± 5.7	23.4 ± 8.0	0.484	0.054

Data are presented as mean ± standard deviation. Between-group differences were assessed using one-way analysis of variance.

Table 1. Participants' baseline morphometric characteristics.

Variable	EMS anterior	EMS whole	Control	p-value	η²
CMJ height (cm)	28.8 ± 6.3	28.2 ± 6.7	25.4 ± 6.0	0.465	0.057
SLJ length (cm)	151.2 ± 17.8	146.6 ± 27.7	144.3 ± 14.4	0.767	0.020
CS-30 score (times)	37.4 ± 6.6	38.9 ± 6.0	35.2 ± 2.7	0.308	0.087
MIKE torque at 20° (Nm)	54.0 ± 13.8	47.7 ± 11.9	51.1 ± 14.7	0.605	0.038
MIKE torque at 45° (Nm)	101.1 ± 37.3	90.4 ± 26.7	97.8 ± 30.1	0.746	0.022
MIKE torque at 70° (Nm)	124.6 ± 47.0	134.0 ± 45.5	118.3 ± 33.4	0.708	0.026
MIKF torque at 20° (Nm)	60.5 ± 29.8	58.6 ± 20.8	50.9 ± 24.6	0.678	0.029
MIKF torque at 45° (Nm)	65.6 ± 26.5	62.1 ± 17.1	53.3 ± 19.3	0.434	0.062
MIKF torque at 70° (Nm)	64.8 ± 20.9	54.0 ± 9.9	47.5 ± 13.4	0.061	0.194

Data are presented as mean ± standard deviation. Between-group differences were assessed using one-way analysis of variance. Angles indicate the knee joint angle at which torque was measured (maximum knee extension = 0°).

Table 2. Baseline measurements of the jump parameters, CS-30 score, and muscle strength.

were connected with a 10-cm line on which the participants marked the degree of soreness[32] 1 day after each training session. Simultaneously, the location of muscle soreness was identified using a human anatomy chart with anterior and posterior views.

Statistical analysis

The data are represented as mean ± standard deviation. To assess the effect of the PIC exercise with EMS applied to the two muscle areas on anthropometric data, jump parameters, CS-30, MIKE and MIKF torques, and muscle soreness, a two-way [group (EMS anterior, EMS whole) x time (Pre, Post 3W, Post 6W)] repeated-measures analysis of variance (ANOVA) with Bonferroni post-hoc test was used. Differences in these measurements between the three groups (EMS anterior, EMS whole, control) at Baseline were assessed using one-way ANOVA with Bonferroni post-hoc test. Levels of significance were set for $p<0.05$. Eta squared (η^2) was used to estimate the effect size of the interaction and main effects with <0.06 indicating a small, 0.06 to 0.14 a medium, and >0.14 a strong effect. The effect size (r) of the

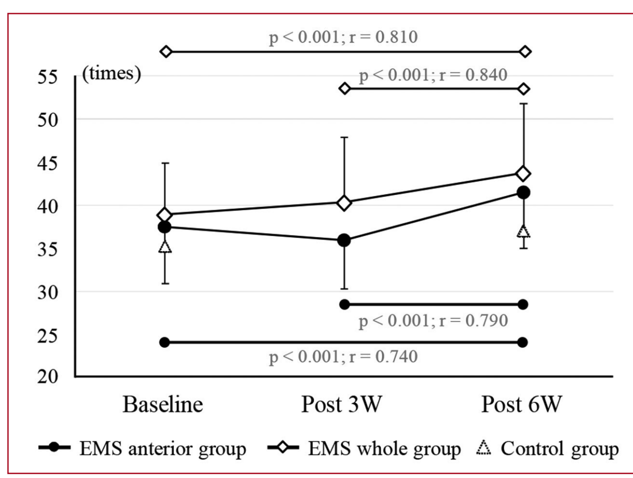

Figure 2. Scores in the 30s chair stand test (CS-30) at Pre, Post 3W, and Post 6W. Horizontal lines placed above or below the error bars indicate significant differences between Pre, Post 3W, and Post 6W (p: probability, r: effect size). In the case of the control group, only the mean values are provided for reference.

Time	Group		Interaction		Main effect			
	EMS anterior	EMS whole	(group x time)		(group)		(time)	
			F-value		F-value		F-value	
			p-value	η^2	p-value	η^2	p-value	η^2
MIKE torque at 20° (Nm)								
Baseline	54.0 ± 13.8	47.7 ± 11.9	0.231		1.183		12.766	
Post 3W	45.7 ± 18.1	41.8 ± 12.6	0.795	0.003	0.292	0.041	< 0.001	0.155
Post 6W	61.7 ± 15.1	54.0 ± 11.0						
MIKE torque at 45° (Nm)								
Baseline	101.1 ± 37.3	90.4 ± 26.7	0.200		0.718		11.353	
Post 3W	81.0 ± 27.2	76.2 ± 23.9	0.820	0.003	0.409	0.025	< 0.001	0.154
Post 6W	110.9 ± 24.3	99.7 ± 20.5						
MIKE torque at 70° (Nm)								
Baseline	124.6 ± 47.0	134.0 ± 45.5	0.730		0.005		10.309	
Post 3W	106.2 ± 35.7	108.5 ± 40.7	0.490	0.007	0.948	0.000	< 0.001	0.098
Post 6W	143.7 ± 41.4	135.7 ± 46.3						
MIKF torque at 20° (Nm)								
Baseline	60.5 ± 29.8	58.6 ± 20.8	0.517		0.371		7.414	
Post 3W	52.2 ± 26.3	46.3 ± 20.3	0.601	0.005	0.551	0.017	0.002	0.066
Post 6W	66.5 ± 12.8	57.5 ± 17.4						
MIKF torque at 45° (Nm)								
Baseline	65.6 ± 26.5	62.1 ± 17.1	0.870		0.236		4.595	
Post 3W	56.7 ± 21.3	56.7 ± 17.3	0.428	0.008	0.633	0.011	0.017	0.042
Post 6W	69.2 ± 14.4	61.2 ± 13.5						
MIKF torque at 70° (Nm)								
Baseline	64.8 ± 20.9	54.0 ± 9.9	2.111		1.400		5.402	
Post 3W	55.4 ± 15.5	54.0 ± 16.3	0.137	0.020	0.253	0.059	0.009	0.051
Post 6W	68.4 ± 15.6	58.0 ± 11.7						

Data are presented as mean ± standard deviation. Angles indicate the knee joint angle at which torque was measured (maximum knee extension = 0°).

Table 3. Maximum isokinetic knee extension and flexion torque in the EMS-applied groups.

post-hoc test was used with <0.30 indicating a small, 0.30 to 0.50 a medium, and >0.50 a strong effect. Significant differences in anthropometric data, jump parameters, CS-30, and MIKE and MIKF torque between times (Baseline, Post 6W) of the control group were assessed using a two-sided paired t-test. Levels of significance were set for $p<0.05$. The effect size (r) between Baseline and Post 6W was used with <0.30 indicating a small, 0.30 to 0.50 a medium, and >0.50 a strong effect.

Results

One of the 30 participants assigned to the EMS anterior group withdrew from the study due to suspected coronavirus disease 2019 after the baseline-test. The morphometric characteristics of the participants are shown in Table 1. There were no significant differences among the three groups for any variables at baseline ($p>0.126$, $\eta^2<0.148$). These variables did not show significant changes throughout the training period in all three groups. Furthermore, there were no significant differences in measurements among the three groups at baseline ($p>0.061$, $\eta^2<0.194$). The baseline measurements of the jump parameters, CS-30 score, and muscle strength are presented in Table 2. During the training period, no adverse events related to the application of EMS were observed. The participants reported a significant reduction in the pain induced by EMS when it was applied to the muscles during the PIC exercise, as compared to the isometric condition.

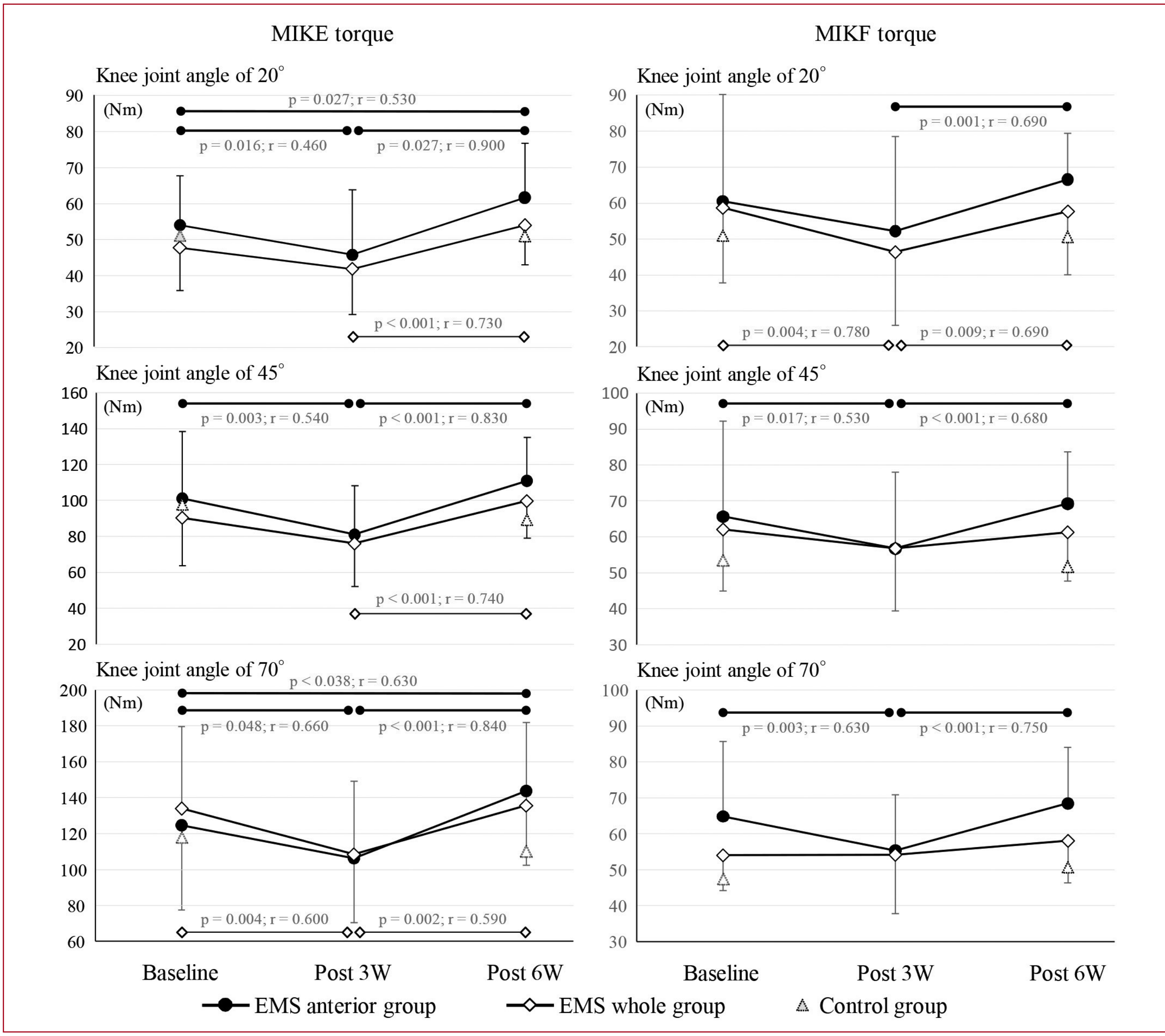

Figure 3. The maximum isometric knee extension (MIKE) and flexion (MIKF) torques at Pre, Post 3W, and Post 6W. Horizontal lines placed above or below the error bars indicate significant differences between Pre, Post 3W, and Post 6W (p: probability, r: effect size). In the case of the control group, only the mean values are provided for reference.

Jump parameter

The CMJ height and SLJ length did not change significantly throughout the training period in the EMS-applied groups. The CMJ height also showed no significant changes in the control group; however, the SLJ length significantly decreased by 6.3 ± 7.3% after the training period (at Post 6W) (t_9=2.718; p=0.024; r=0.670).

CS-30 score

A repeated two-way ANOVA in the EMS-applied groups showed no significant interaction for the CS-30 score ($F_{2,51}$=1.830; p=0.176; η^2=0.008) (Figure 2). A significant main effect was observed for the time factor ($F_{2,51}$=20.583; p<0.001; η^2=0.091), with a significant increase in its score from Post 3W to Post 6W for the EMS anterior (16.1 ± 13.0%) and whole groups (12.4 ± 11.3%)

and from Baseline to Post 6W (11.3 ± 9.3% and 8.8 ± 7.0%, respectively). No significant differences were found in the control group before and after the training period.

Maximum isometric knee extension and flexion torque

The MIKE and MIKF torque measured at baseline, Post 3W, and Post 6W in the EMS-applied groups are presented in Table 3. No significant interaction was observed between the MIKE and MIKF torques in the EMS-applied groups at all knee angles measured. Significant main effects were observed for time factors of knee joint angles of 20°, 45°, and 70° for the MIKE torque and 20°, 45°, and 70°for the MIKF torque. The MIKE torque decreased significantly from Baseline to Post 3W at 20° (-14.0 ± 26.9%), 45° (-7.3 ± 44.4%), and 70° (-5.6 ± 35.6%) and increased significantly from Post 3W to Post 6W at 20° (42.1 ± 29.5%), 45° (44.4 ± 34.8%), and 70° (41.7 ± 35.9%) in the EMS anterior group. It also increased significantly from Baseline to Post 6 W at 20° (18.1 ± 28.1%) and 70° (33.8 ± 66.4%). The EMS whole group showed a significant increase in the MIKE torque from Post 3W to Post 6W at 20° (38.9 ± 44.5%), 45° (46.2 ± 69.6%), and 70° (40.8 ± 66.2%) and a significant decrease from Baseline to Post 3W at 70° only (-17.3 ± 22.8%) (Figure 3 left). The MIKF torque showed smaller changes than the MIKE torque (Figure 3 right). The EMS anterior group showed a significant increase in the MIKF torque from Post 3W to Post 6W at 20° (68.0 ± 102.9%), 45° (39.3 ± 60.5%), and 70° (11.7 ± 24.1%) and a significant decrease from Baseline to Post 3W at 45° (-8.3 ± 23.0%) and 70° (-11.5 ± 16.9%). The EMS whole group showed a significant decrease in the MIKF torque from Baseline to Post 3W (-22.1 ± 18.6%) and a significant increase from Post 3W to Post 6W (41.4 ± 61.7%;) at 20° only. The control group showed no significant differences between Baseline and Post 6W.

Muscle soreness

No significant interaction on muscle soreness after nine training sessions was observed in the EMS-applied groups. Significant main effects were found between the groups ($F_{1,153}$=12.523; $p<0.003$; η^2=0.207) (Figure 4). Muscle soreness was significantly greater in the EMS anterior group than in the EMS whole group after all training sessions from sessions 1–9 (all $p<0.001$; r=0.380–0.730). However, the soreness was small: 3.0 ± 0.6 cm in the EMS anterior group and 0.7 ± 0.6 cm in the EMS whole group. None of the participants in the control group reported muscle soreness throughout the training period.

The locations where the EMS anterior group clearly perceived muscle soreness were the lower electrode attachment areas of the anterior thigh muscles, particularly the vastus medialis muscle (21.0% of nine participants × nine training sessions = 81 times) and its upper electrode attachment areas (2.5%). Other locations where they felt sluggish, rather than soreness, were the entire anterior thigh muscles (14.8%) and the entire posterior thigh muscles (3.7%). Two participants noted that they began to feel sluggish in their legs, though not painful, after week 5 when the EMS intensity increased by one step.

The EMS whole group noted that muscle soreness occurred at the electrode attachment points on the anterior thigh muscles, particularly the lower part (23.3% of 10 participants × nine training sessions = 90 times), and on the anterior and posterior thigh muscles (4.4%). Two participants noted that they began to feel sluggish in their legs, though not painful, after week 6 when the EMS intensity increased by two steps. In both groups, the participants tended to report pain or sluggishness in the same locations throughout the training sessions.

Kinesthesia in daily life

None of the participants in the control group reported a difference in their kinesthesia in daily life between Baseline and Post 6W; no participants in the EMS-applied groups also reported such a difference at Post 3W. However, seven of the nine participants in the EMS anterior group reported feeling a sensation of being “lighter to move” at Post 6W. Of the seven participants, four reported experiencing “more strength in the legs,” two reported finding it “easier to climb stairs,” and one reported finding it “easier to ride a bicycle up a hill.” Similarly, seven of the ten participants in the EMS whole group also reported feeling a sensation of being “lighter to move” at Post 6W. Of the seven participants, four reported experiencing “more strength in the legs,” three reported finding it “easier to climb stairs” and two reported that they could “walk faster.”

Discussion

PIC exercise without EMS

The PIC exercise is a passive training method that requires no effort or physical exertion, making it easy to perform and carrying a low risk of injury. Repetitive passive movements, although less effective than voluntary movements, improve cortical excitability[33-35], proprioception[36], muscle blood flow[37], and capillary growth[38]. However, the PIC exercise without EMS decreased the MIKE and MIKF torques at many knee joint angles. The participants’ kinesthesia in daily life also remained unchanged. Because passive exercises have been reported to increase the passive range of motion[33], the decrease in the efficiency of muscle tension transmission due to increased flexibility may have led to these outcomes. Therefore, the PIC exercises without EMS appeared to be an optimal method for sedentary individuals to adapt to training while improving their nervous system, cardiovascular system, and flexibility, especially during the introductory phase.

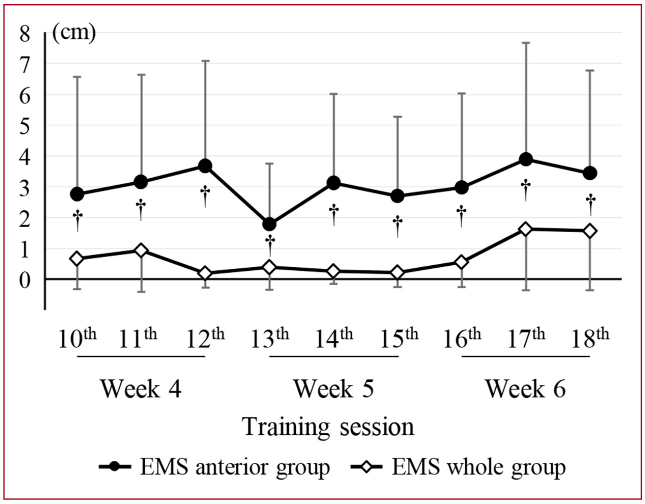

Figure 4. Changes in muscle soreness during the training period. Daggers (†) indicate a significant difference between EMS anterior and whole groups ($p<0.001$).

PIC exercise with EMS

Recent studies[39] on the application of whole-body EMS, which can simultaneously stimulate large muscle areas, have reported that initial whole-body EMS at excessively high intensity leads to a significant increase in serum creatine kinase concentrations, suggestive of rhabdomyolysis; however, it is ameliorated by the subsequent repetition of the exercise. Therefore, the intensity of EMS combined with PIC exercises was initially set at the lowest possible level of approximately 2.5 mA to prevent any discomfort, pain, and muscle damage caused by EMS. It was then gradually increased to a final level of approximately 3.0 mA. Although differences in EMS conditions, such as frequency, pulse width, waveform, electrode, and stimulation time, make comparisons of the EMS intensity between this study and previous studies[40] difficult, the current values applied in this study were considerably low. Low levels of muscle soreness throughout the training period suggest its low EMS intensity.

The EMS frequency was set to 20 Hz for the following reasons: 1) unstable muscle tension at frequencies lower than 20 Hz, 2) immediate muscle fatigue at frequencies higher than 50 Hz[41], and 3) light kinesthetic sensations during jumps at 20 Hz[42]. The pulse width of 260 μs was selected based on feedback from participants in another experiment[42], who indicated that they were most comfortable performing the exercises when EMS was applied to the muscles at its width. These EMS conditions, including the waveform, pulse width, and electrode, significantly reduced the prickling pain commonly experienced by the participants during EMS. Furthermore, the participants reported a significant reduction in pain induced by EMS during the PIC exercise, indicating that movement also played a role in alleviating the pain.

Numerous previous studies[27,43] have reported that EMS exercise, especially when combined with voluntary exercise, improves muscle strength. In this study, the MIKE and MIKF torques significantly increased once EMS, as described above, was superimposed on the thigh muscles during the PIC exercise. Considering that the PIC exercise with EMS was performed at low EMS intensities, for a short time (10 min) and a short period (3 times a week for 3 weeks), it can be inferred that the torque was increased by the following features of the PIC exercise and EMS: 1) reduction of the disadvantage of EMS recruiting muscle fibers in a superficial and limited area by changes in the position of the EMS electrodes placed on the skin relative to the muscles caused by the passive movement[44], that is, recruitment of muscle fibers in a wider area[45]; 2) the synchronization of muscle fiber contraction[24], nonselective muscle fiber recruitment from the low exercise intensity[25], and the activation of the central nervous system[26]. The participants' reports of "feel sluggish in the thighs after the exercise" and mild muscle soreness resulting from the exercise may be attributed to the EMS causing more extensive muscle contractions during passive exercise. Therefore, the results of this study suggest the potential for improving muscle strength even when combining EMS with completely passive isokinetic exercise, rather than voluntary exercise. This implies that the PIC exercise may be a beneficial means for individuals in inadequate environments for voluntary exercise or who are not good at performing exercises to initiate and maintain physical activity.

Muscle area where EMS was applied

EMS was applied to the lower limb muscles, including antigravity muscles that experience significant muscle mass decline with age[46]. In the EMS anterior group, EMS was applied to the quadriceps muscles, which show a particularly notable decrease[47]. On the other hand, in the EMS whole group, EMS was applied to the entire thigh muscles, including both agonist and antagonist muscles, for the following reasons: throughout passive pedaling 1) alternating passive shortening and lengthening contractions can be induced, and 2) passive contractions of the synergist and antagonist muscles can provide resistance to each other[48].

The severity of muscle soreness depended on the area of muscles where EMS was applied during the PIC exercise; however, it was not severe in either case. The EMS anterior group had significantly greater muscle soreness than the EMS whole group throughout the training period. The soreness that particularly occurred under the small-area electrode attached to the distal end of the target muscles (particularly the vastus medialis muscle) was more clearly perceived in the EMS anterior group, suggesting that it depended on the electrode location[49] relative to the muscle motor points and current density.

In contrast, training-induced changes in the knee joint torque, CS-30 scores, and jumping ability were similar in both groups. Such outcomes obtained under different current densities may be the result of the nonselective recruitment of many muscle fibers from the lower EMS intensities during the PIC exercise[13,44-45]. The training method for repeated passive shortening and lengthening contractions with EMS must also have contributed to the improvement in the knee joint torque and CS-30 scores. It is suggested that superimposing EMS on the entire thigh muscles during the PIC exercise has particularly compensated for the disadvantage of small current density on the training effect by co-contracting the anterior and posterior thigh muscles and loading them against each other's contractions[19]. Therefore, the EMS superimposition on the entire thigh muscles would produce similar training effects to that on the anterior thigh muscles with less muscle soreness.

Effects of PIC exercise with EMS on multi-joint movements

The CS-30 is a useful test for assessing lower body strength using movements that are commonly used in daily life. Its scores are correlated with maximal leg press performance[50]. The PIC exercise with EMS increased the CS-30 scores, but it did not increase the jump height of the CMJ and SLJ. The effects of EMS alone have location-specific and non-speed-specific features that do not facilitate learning-specific coordination of complex movements[51]. These suggests that the combination of EMS and completely passive isokinetic exercise improves muscle strength and basic daily movements, whereas it does not lead to improvements in more challenging movements, such as jumping, which require short bursts of power, high intensity, and precise coordination of motor control. The PIC exercise with EMS was different in both purpose and method from functional electrical stimulation (FES) cycling in which EMS was applied to the lower limb muscles at appropriate times to generate cyclical muscle contractions to propel the cycle ergometer to improve muscle strength and motor control[52-54]. The PIC exercise was developed with the objective of improving muscle strength and reducing the strain of daily activities, while minimizing difficulties, effort, and exertion. Therefore, the PIC exercise with EMS alone is insufficient to improve various movements, and its improvement would require exercises that include the muscle coordination pattern of each movement.

However, the findings, such as the negative correlation between muscle strength and higher echo intensity, which indicates lower muscle quality, in individuals with smaller muscle mass, slower gait ability, and lower physical activity[55,56], and the strong correlation between muscle strength and motor function in muscular dystrophy[57], suggest that the increase in muscle strength may potentially contribute to the improvement of multi-joint movement control required for challenging physical exercises. Therefore, there is a possibility that if the PIC exercise is performed with higher EMS intensities over a longer period, the potential contribution to their performance improvement could be increased.

Effects of PIC exercise with EMS on kinesthesia in activities of daily life

The results of the free-description questionnaire survey indicated that approximately 70% of the EMS-applied groups reported changes in kinesthesia during daily life after the PIC exercise with EMS (after Post 6W). These changes included feelings of "greater leg strength" and "lighter movement." In contrast, no similar descriptions were reported after the PIC exercise without EMS (after Post 3W) or in the control group. These findings suggest that enhanced muscle strength can improve kinesthetic perception, thereby facilitating the performance of daily physical activities such as "stair climbing" and "walking." This facilitation may help overcome common barriers that prevent people from engaging in physical activity[22]. Furthermore, it has the potential to reduce physical inactivity, which is a significant underlying factor of sarcopenia[1] and frailty[58]. However, this study lacks a validated outcome measure to confirm this hypothesis. Therefore, further research is needed to elucidate the specific effects on muscle strength, kinesthesia, and subsequent physical activity.

Study limitations

The PIC exercise with EMS improved the participant's muscle strength and kinesthesia in daily life without any effort or severe muscle soreness. However, a more accurate evaluation of the PIC exercise with EMS requires further research to address the following aspects: 1) assessing not only short-term and low-intensity training but also long-term and high-intensity training, including examining its long-term effects and determining appropriate EMS intensity, among physiological variables; 2) evaluating the training effect on older individuals and those in inadequate environments for voluntary exercise or who are not good at performing exercises; 3) evaluating the training effects on individuals at various stages, such as those in presarcopenia, sarcopenia, and severe sarcopenia[1]; and 4) investigating changes in daily activities following the training.

A double-blind method was unable to be implemented in this study due to the application method of EMS. Applying EMS to the muscles during the PIC exercise resulted in a decrease in stimulus perception. Therefore, to achieve blinding, it is necessary to improve the electrodes in such a way that it is not discernible which muscles are being stimulated.

Conclusions

The PIC exercise with EMS applied to the thigh muscles efficiently improved muscle strength without requiring any effort or causing severe muscle soreness and facilitated a perceived ease in daily physical activities. Particularly, applying EMS to the entire thigh muscles resulted in similar improvements in muscle strength while causing less muscle soreness compared to applying EMS to the anterior thigh muscles. These results indicate that the PIC exercise with EMS may provide a simple and effective method to engage in exercise, particularly for individuals who are in inadequate environments for voluntary exercise or who are not good at performing exercises, because it can improve muscle strength while reducing various barriers to exercise habits. This also suggests that it may serve as an effective approach to prevent diseases such as sarcopenia, frailty, and disuse muscle atrophy.

Ethics approval

The study complied with the Declaration of Helsinki 1964 "Ethical Principles for Medical Research Involving Human Subjects" and was approved by Ethics Committee of Aoyama Gakuin University (A020-1/2020).

Consent to participate

All participants provided written informed consent after being fully informed of the nature and possible consequences of this study.

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Authors' contributions

All authors were responsible for the study conception and design, statistical analyses, the interpretation of data, and manuscript drafting. Kazuyuki Ogiso reviewed the manuscript. All authors approved the final version of the manuscript.

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