The effect of electrical muscle stimulation on quadriceps muscle strength and activation patterns in healthy young adults

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Title

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Abstract

The aim of the present study was to clarify the effect of electrical muscle stimulation (EMS) on the spatial distribution pattern of electromyographic activity in healthy young adults using multi-channel surface electromyography (SEMG). A total of 32 men (age =21–26 years) were randomly assigned to the intervention group (n=18) and control group (n=14). Participants in the intervention group performed EMS to stimulate the bilateral lower limb muscle for four weeks (20 min/3 days/week). The control group received no EMS intervention. To understand the effects of EMS, following measurements were made at baseline and four weeks: knee extension torque, muscle mass, and spatial distribution of neuromuscular activation during a target torques [10%, 30%, 50%, and 70% of the maximal voluntary contraction (MVC)] using multi-channel SEMG. The knee extension torque was significantly increased in intervention group compared with control group ($p < 0.0001$). However, the muscle mass did not show a significant difference between pre and post intervention in each group.

The muscle activation patterns of 50% and 70% MVC task showed significant enhancement between baseline and four weeks in the intervention group. Furthermore, a moderate correlation between Δ knee extension torque and Δ spatial distribution pattern of electromyographic activity of 50% and 70% MVC in the intervention group was observed. These results suggested EMS intervention induced different distribution of muscle activity at high-intensity muscle contraction compared with low-intensity muscle contraction.

Introduction

An improvement of muscle performance with training is due to the adaptation of morphological and neural factors [1]. Especially, neural factors are the major contributors to increase strength during the early phase of training [2]. Many previous studies reported that resistance training enhanced muscle strength and muscle thickness [1, 3, 4]. In general, the morphological factors can be assessed by the measurements of muscle mass with magnetic resonance imaging [3, 5]. Recently, the change of neural factors during resistance training have been reported by measurements of motor unit activity using multi-channel surface electromyography (SEMG) [6]. This technique provides data on the spatial distribution of SEMG within a muscle. Previous studies using this technique have demonstrated that the spatial SEMG potential distribution pattern within a muscle is altered by contractions or fatigue level [7, 8]. This phenomenon has been explained by spatial inhomogeneity in the location of different types of muscle fibers [9]. Previous studies have also demonstrated that changes in the spatial distribution of multi-channel SEMG can be explained by the physiological phenomenon of motor unit recruitment, which suggests that the spatial distribution of multi-channel SEMG can be used to study changes in motor unit recruitment [10, 11]. Although, previous studies reported that increase in the SEMG amplitude due to resistance training [1, 3, 12], spatial distribution pattern of muscle activation did not change during resistance training using multi-channel SEMG [6]. These results suggested that the spatial distribution of neuromuscular activation is not influenced by resistance training.

It is widely known that electrical muscle stimulation (EMS) interventions can improve muscle performance and muscle thickness [13-18]. The previous studies speculated that the EMS intervention induced non-physiological recruitment order and synchronous discharge of motor units [19-21]. In general, according to the size principle, voluntary motor unit recruitment describes the progressive recruitment of small, typically slow motor units followed in order of increasing size to the large, typically motor units [22, 23]. However, EMS recruits motor units randomly in relation to axon diameter [24]. It indicates that muscle activation differs between voluntary and electrically-induced contraction.

The purpose of the present study was to clarify the effect of EMS intervention on spatial distribution of neuromuscular activation in healthy young adults. We hypothesized that EMS intervention induced improvement of muscle strength and different distribution of muscle activity.

Materials and Methods

Participants

A total of 32 males were randomly assigned to the intervention group (n = 18; age = 21–26 years; height = 171.1 ± 4.4 cm; body mass = 65.1 ± 7.7 kg) and control group (n = 14; age = 21–27 years; height = 170.3 ± 4.9 cm; body mass = 63.8 ± 5.9 kg). Our previous study showed that compared with healthy young male, healthy young female exhibited greater differences in the spatial distribution patterns of muscle activation using multi-channel SEMG during sustained isometric contraction [25]. This finding suggests that it is necessary to differentiate between males and females when assessing muscle activation pattern using multi-channel SEMG. Therefore, we included only male in the current study. The exclusion criteria were patients with neuromuscular disease, cardiovascular disease, and diabetes mellitus. All procedures were performed in accordance with the Declaration of Helsinki and were approved by Hiroshima University's Committee on Ethics in Research (C-273). All participants signed an informed consent form and consented to the publication of this work. The following measurements were made at baseline and 4 weeks for all participants: muscle strength, muscle mass, and multi-channel SEMG measurement.

Experimental design

Participants in the intervention group underwent EMS of the quadriceps muscle of both legs for 4 weeks. Muscles were stimulated at a frequency of 20 Hz with a monophasic square-wave pulse of 250 μs duration using an EMS device

(AUTO TENS PRO Rehabili Unit, Homer Ion Co., Ltd., Tokyo, Japan). The stimulation intensity was individually set to the maximal level without discomfort in each subject. EMS was performed a lying position for 3 days per week. The device was positioned at the trunk and mid-point of the femur and thigh for 20 min once per day. Participants were instructed not to actively contract muscles during the stimulation. Those in the control group did not undergo any intervention. Although the EMS intervention was applied to both legs, the following test measurements were made on a single test leg (e.g., dominant side). To estimate the effects of EMS, the following measurements were made at baseline and four weeks: maximal voluntary knee extensor contraction strength, vastus lateralis (VL) muscle spatial distribution of neuromuscular activation during a submaximal isometric knee extension using multi-channel SEMG, and muscle mass.

Maximal voluntary strength

All participants performed maximal voluntary contractions (MVCs) during isometric knee extension at baseline and 4 weeks. Isometric knee extension was performed using a Biodex system (Biodex System 4; Biodex Medical Systems, Shirley, NY, USA). During contraction, both the hip and knee extension angles were fixed at 90˚. The MVC involved a gradual increase in knee extension torque exerted by the knee extensor muscles from 0 to maximum over 3 s, with the maximum torque held for 2 s [18, 26]. The participants performed at least two MVC trials with a 2 minutes rest between trials, and a warm up for 10 min, including indoor walking and lower limb stretching before MVC measurement. The highest MVC torque was used to calculate the MVC torque and target torque for sustained contractions. All participants performed submaximal isometric contractions at 10%, 30%, 50%, and 70% MVC in a randomized order with a 2 minutes rest between trials. The contractions at 10% and 30% were sustained for 20 sec, 50% MVC was sustained for 15 sec, 70% MVC was sustained for 10 sec, and the rising phase and decline phase for 5 sec[27]. This assessment was performed at baseline and 4 weeks.

Measures of muscle mass

Measurements of muscle mass were performed using direct segmental multifrequency bioelectrical impedance analysis (InBody S10, InBody Japan, Tokyo, Japan). It is a validated method for estimating skeletal muscle mass comparable to dual-energy X-ray absorptiometry [28]. All participants were attached electrode on bilateral thumb, middle finger, and ankle, and asked to lie down in supine position with straightened arms and legs whenever able and to lie as still as possible during the measurements. This assessment was performed at baseline and 4 weeks.

SEMG recording

The participant performed a maximum isometric knee extension contraction. During the maximal contraction, multi-channel SEMG signals were detected from the dominant VL muscle using a semi-disposable grid of 64 electrodes (ELSCH064NM2; OT Bioelettronica, Torino, Italy) according to the same procedure used in previous studies [18, 25, 29]. The grid consisted of 13 columns and five rows of electrodes (diameter, 1 mm; inter-electrode distance, 8 mm in each direction), with one missing electrode in the upper left corner. The participants hair was removed, the skin was cleaned with alcohol, and the electrode was attached to the skin with a bi-adhesive sheet (KITAD064NM2; OT Bioelettronica) after applying conductive paste (Elefix Z-181BE; NIHON KOHDEN, Tokyo, Japan) corresponding to the placement of the electrodes. The center of the electrode grid was attached at the center of the line between the superior lateral edge of the patella and the greater trochanter protuberance. The columns of the electrode grid were placed parallel to the longitudinal axis of the VL muscle. Participants were made a mark on the position where the electrode was attached with an oil-based marker and asked to keep the mark until the end of the study period. The site of the missing electrode was placed proximal to the

VL muscle. A reference electrode was attached at the anterior superior iliac spine. All procedures were performed by the same investigator.

Monopolar multi-channel SEMG signals were amplified by a factor of 1000, sampled at 2048 Hz per channel, and converted to digital data using a 12-bit analog-to-digital converter (EMG-USB2+; OT Bioelettronica). The recorded monopolar multi-channel SEMG signals were off-line bandpass-filtered (10–500 Hz) and transferred to software for analysis (MATLAB 2018b; Math Works GK, Natick, MA, USA). Bipolar multi-channel SEMG signals (n = 59) along the columns were divided from the 64 electrodes. To calculate the root mean square (RMS) of multi-channel SEMG signals, the signals were sampled at the submaximal voluntary contraction task (e.g., 10%, 30%, 50%, and 70% MVC task). To control for inter-participant variability, we normalized the RMS measures to the values obtained at MVC.

To characterize the heterogeneity in the spatial multi-channel SEMG potential distribution, we determined the modified entropy, coefficient of variation (CoV), and the correlation coefficient of spatial RMS estimates. The modified entropy of the spatial distribution of the SEMG amplitude was calculated for 59 RMS values of single differential signals computed over a 1-s period taken at the time of the contraction during the isometric sustained contraction. Using the methods of Farina et al., [7] modified entropy was calculated for 59 RMS measurements and average of 59 RMS measurement.

The CoV of spatial RMS estimates was defined as the quotient of the standard deviation of the 59 RMS measurements and the average of 59 RMS measurement. For submaximal voluntary contraction, modified entropy and CoV of RMS at 50% of contraction time, and correlation coefficients between the spatial distribution pattern of SEMG at 10% and 100% of contraction time were calculated. A decrease in the modified entropy and an increase in the CoV of spatial RMS estimates indicated increased heterogeneity in the spatial multi-channel SEMG potential distribution within the electrode grid [30]. We calculated the percent change in modified entropy, CoV and correlation coefficient measures from baseline at 4 weeks.

Statistical analysis

Statistical analyses were performed using GraphPad Prism 8 (GraphPad Software Inc, San Diego, CA, USA). The continuous data are presented as the mean ± standard deviation or the median (minimum, maximum). Before the analysis, the normal distribution of data was confirmed using the Shapiro-Wilk test. Age, height, body mass, and muscle mass were compared between the intervention and control groups using unpaired *t*-tests. Statistical differences in maximal knee extension torque, muscle mass, absolute value of RMS, modified entropy, CoV of RMS, and correlation coefficient of submaximal voluntary contraction tasks (e.g., 10%, 30%, 50%, and 70% MVC task) were analyzed using two-way (group (intervention and control) vs. period (pre and post)) analysis of variance (ANOVA) with repeated measure. The differences between each group and/or period were analyzed by Bonferroni post hoc test. Pearson's correlation coefficients were computed to assess bivariate correlations between the Δ knee extension torque and Δ modified entropy, Δ CoV, and Δ correlation coefficient. The correlation coefficients were qualitatively interpreted according to the following thresholds: 0.2 < 0.4, small; 0.4 <0.7, moderate; 0.7 < 0.9, strong; 0.9 < 1.0, very strong. Two-tailed p values < 0.05 were considered statistically significant.

Results

The general characteristics of the participants are presented in Table 1. There were no significant differences between groups in terms of the anthropometric parameters.

The knee extension torque showed significant interaction between group and period (F (1, 30) = 32.09, $p < 0.0001$). The intervention group showed significantly higher knee extension torque in the post intervention than in the pre intervention ($p < 0.0001$), but not in the control group (Fig.1A and B). The muscle mass did not show a significant interaction between group and period (F (1, 30) = 0.05526, $p = 0.8158$), and not a significant difference between pre and post intervention in each group (Fig. 1C and D).

RMS of 50% and 70% MVC task showed significant interaction between group and period (F (1, 30) = 10.40, $p = 0.0030$, F (1, 30) = 25.45, $p < 0.0001$, respectively). The intervention group showed significantly higher RMS value in the post intervention than in the pre intervention of 50% and 70% MVC, but not in the control group ($p = 0.9908$ and $p = 0.9964$ respectively, Fig. 2).

The modified entropy, CoV, and correlation coefficient of 50% MVC task showed significant interaction between group and period (F (1, 30) = 9.784, $p = 0.0039$, F (1, 30) = 20.13, $p < 0.0001$, F (1, 30) = 37.33, $p < 0.0001$, respectively). The intervention group showed significantly higher CoV and lower modified entropy and correlation coefficient ($p < 0.0001$, respectively) in the post intervention than in the pre intervention of 50% MVC task (Fig. 3 G–I). The modified entropy, CoV, and correlation coefficient of 70% MVC task did not show significant interaction between group and period (F (1, 30) = 2.523, *p* = 0.1227, F (1, 30) = 2.879, *p* = 0.1001, F (1, 30) = 3.253, *p* = 0.0813, respectively). Results of two-way ANOVA, the modified entropy, CoV, and correlation coefficient of 70% MVC task showed significant group factor (F (1, 30) = 5.775, p = 0.0226, F (1, 30) = 5.888, p = 0.0215, and F (1, 30) = 0.0016, respectively, Fig. 2 J–L). The modified entropy, CoV, and correlation coefficient of 10% and 30 % MVC task did not show significant interaction between group and period, and not significant difference between pre and post intervention (Fig. 3 A–F).

Moderate correlations were observed between Δ knee extension torque and Δ modified entropy (r = -0.5741, *p* = 0.0160 and r = -0.5612, *p* = 0.0191), Δ CoV (r = 0.4904, *p* = 0.0457 and r = 0.6015, *p* = 0.0083), and Δ correlation coefficient (r = -0.4913, *p* = 0.0452 and r = -0.7286, *p* = 0.0006) of 50% and 70% MVC task (Fig. 4). The 10% and 30 % MVC task show did not correlation between Δ knee extension torque and Δ modified entropy, Δ CoV, and Δ correlation coefficient for each group.

Discussion

The present study examined the effects of EMS on muscle strength, spatial distribution of neuromuscular activation, and muscle mass in healthy young adults. The principal results of the present study were that EMS of the lower limbs increased muscle strength, and led to more inhomogeneity in spatial muscle distribution patterns at 50% and 70% MVC tasks.

The results of the present study showed that knee extensor torque was significantly increased in the intervention group. On the other hand, muscle mass did not change by EMS for 4 weeks in the intervention group. It is widely known that EMS intervention can improve muscle performance [13-17]. Furthermore, several studies reported that increase in the muscle strength and muscle thickness occurred after EMS intervention [12, 31, 32]. In accordance with the results of the present study, which compared a control group with an intervention group show significantly increased knee extension torque. However, we did not observe the change of muscle mass in the intervention group. We considered that the intervention period is a key factor. Intervention periods of previous studies were set longer than the present study (e.g., 6 weeks [15], 16 weeks [12], and 20 weeks [32]). Furthermore, Singer and Breidhal demonstrated that there were no significant gross morphological changes in the image of computed tomography, following a four-week program of EMS intervention [33]. Therefore, our results suggest early neural adaptations enhanced muscle strength by EMS intervention. Strength performance depends not only on the quantity and quality of the involved muscles, but also upon the ability of the nervous system to appropriately activate the muscles [34]. Consequently, it is considered that muscle strength increased through neural adaptations without enhanced muscle mass.

In addition to the increases in knee extension torque, the results of the present study showed that spatial muscle distribution patterns of 50% and 70% MVC tasks were changed by EMS interventions. We used modified entropy and CoV of spatial RMS estimates to assess the spatial distribution of neuromuscular activation. A decrease in the modified entropy, correlation coefficient and an increase in the CoV of spatial RMS estimates is consistent with increased heterogeneity in the spatial multi-channel SEMG potential distribution within the electrode grid [30]. The spatial distribution of SEMG is altered by contraction levels or fatigue during isometric contraction [7, 35]. Results of the present study showed significantly higher CoV and lower modified entropy and correlation coefficient ($p < 0.0001$, respectively) in the post intervention than in the pre intervention of 50% and 70% MVC tasks in the intervention group. Furthermore, our results showed that significant correlation between Δ knee extension torque and EMG variables (modified entropy, CoV of RMS, and correlation coefficient) of 50% and 70% MVC tasks. In general, according to the size principle, the progressive recruitment of small, typically slow motor units followed in order of increasing size to the large [22, 23]. Many previous studies also reported that EMS intervention induced non-physiological recruitment order and synchronous discharge of motor units [19-21]. Chasiotis et al., reported that EMS induced more activity of metabolic function (glycogen phosphorylase, high energy phosphates, and lactates) on fast twitch muscle fiber than that on slow twitch muscle fiber [36]. Walters et al., reported that EMS induced more increase cross-sectional area on fast muscle fiber than on slow muscle fiber [37]. These findings suggested that EMS is likely to affect fast muscle fibers. Therefore, it is considered that the change of muscle activity distribution pattern occurred in the 50% and/or 70% MVC tasks which requires the activity of fast muscle fiber, as compared with 10% and/or 30% MVC tasks.

The present study has several limitations. First, participants performed EMS intervention only 4 weeks. Previous study showed that significant strength changes can be produced with 3–5 weeks of training without significant morphological changes such as muscular hypertrophy [1]. Further study needs a longer intervention period than 5 weeks. Second, the present study assessed only isometric muscle strength as a physical performance. Therefore, it is considered that it is possible to clarify the impact of EMS intervention on physical performance in the future study by adding dynamic evaluation (e.g., jump and balance assessments). Third, the present study examined only the SEMG method. SEMG amplitude estimates provide only crude estimates of MU recruitment [38]. Therefore, we were unable to evaluate MU recruitment properties in detail. Several recent studies predicted MU recruitment from multi-channel SEMG using convolution kernel compensation [27, 39]. Further studies using additional analysis methods are needed to elucidate the detailed mechanisms underlying the effect of EMS intervention on MU recruitment patterns.

Conclusions

We investigated that effects of EMS on muscle strength and activation patterns in young adults. The results of the present study indicate that EMS intervention induced enhance muscle strength and different distribution of muscle activity at 50% and 70% MVC tasks.

Conflicts of Interest

The authors declare no conflict of interest and that no companies or manufacturers will benefit from the results of this study.

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Figure legends

Fig. 1

Results of knee extension torque and muscle mass at pre and post intervention in each group.

Fig. 2

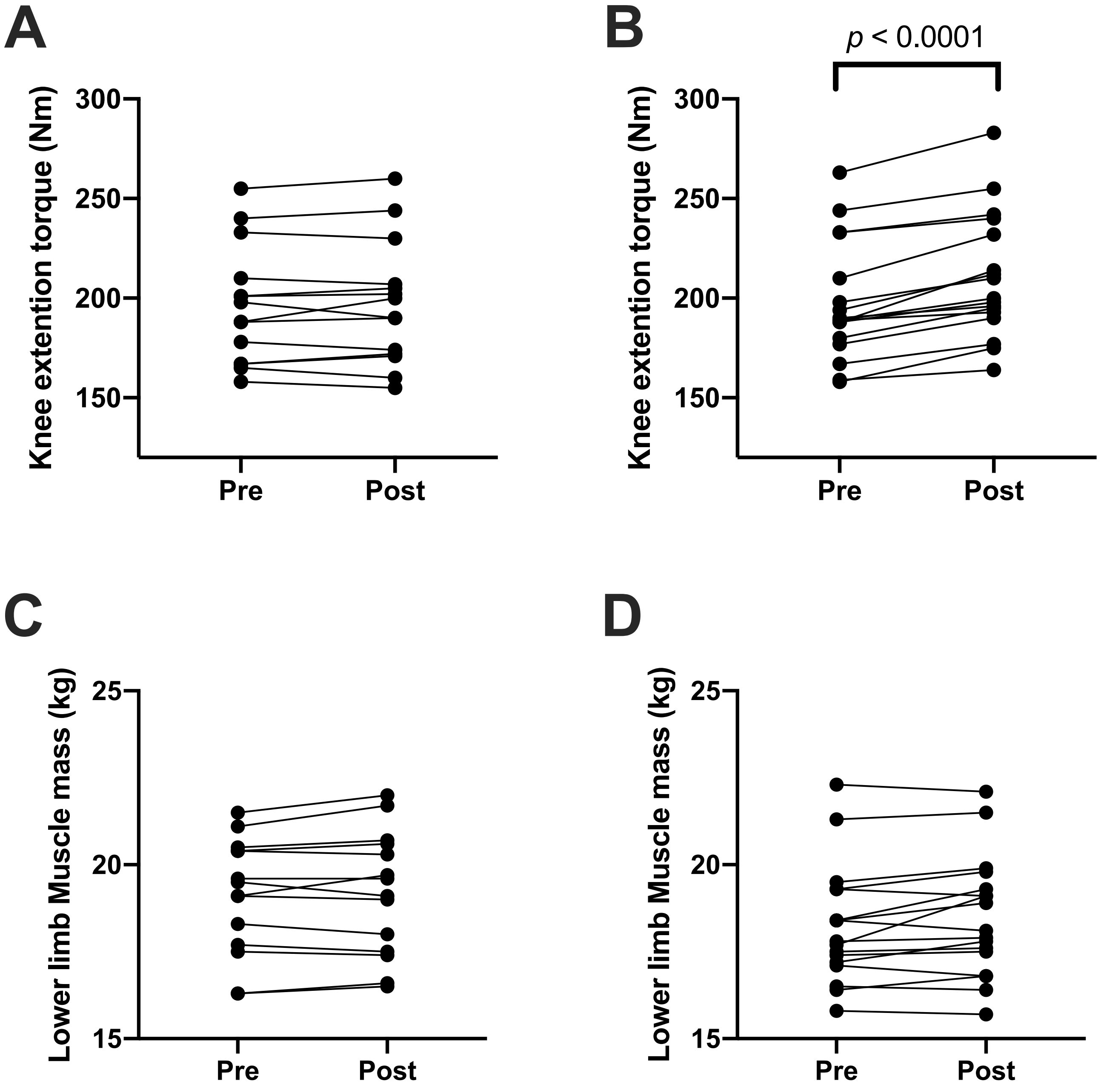
Results of root mean square of all channels during submaximal voluntary contraction (10%, 30%, 50%, and 70%). Data are presented as mean ± SD. * $p < 0.05$.

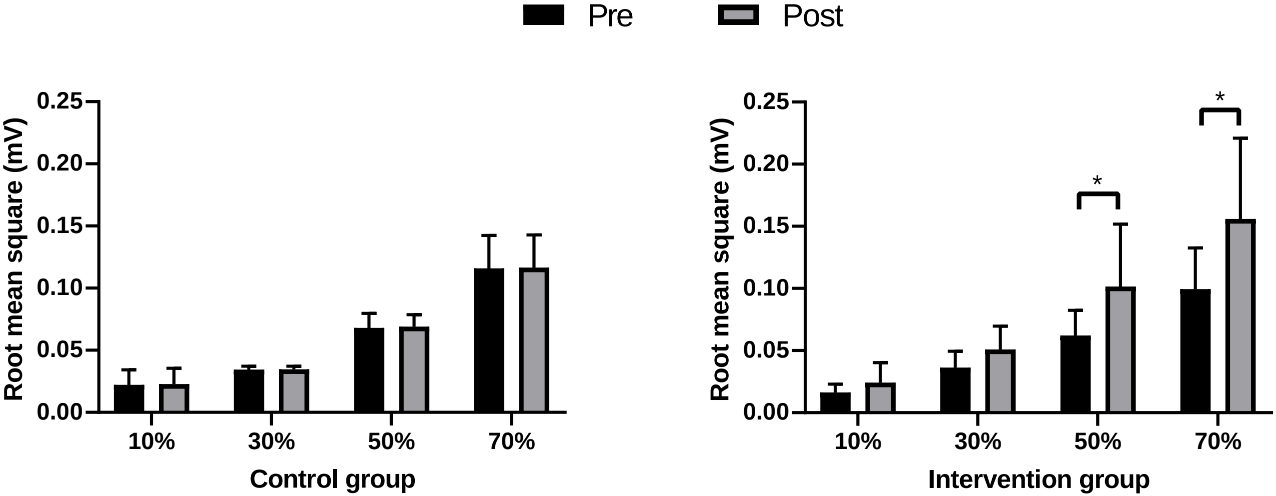
Fig. 3

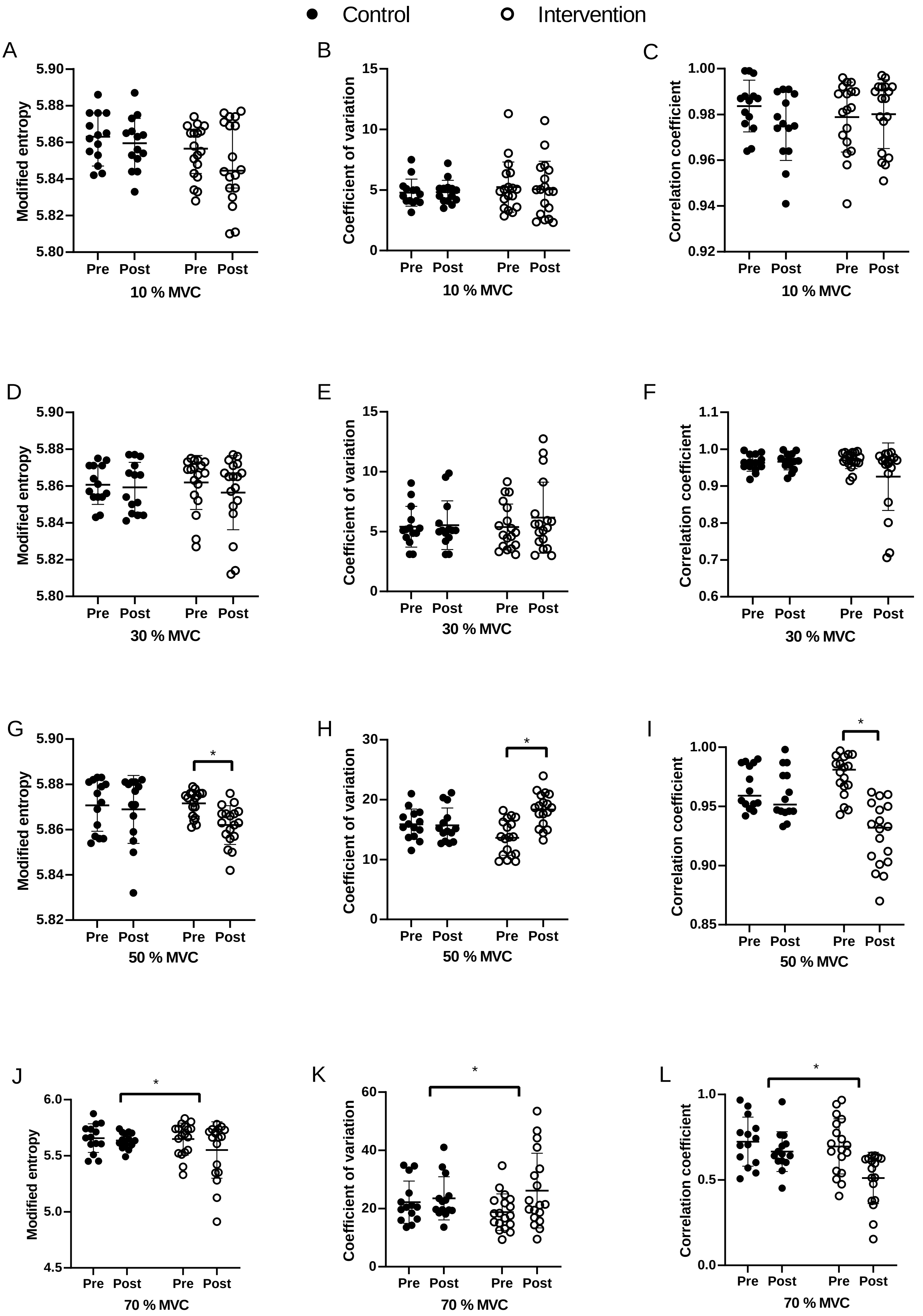
Results of modified entropy, coefficient of variation, and correlation coefficient of submaximal voluntary contraction at pre and post intervention in each group. * $p < 0.05$.

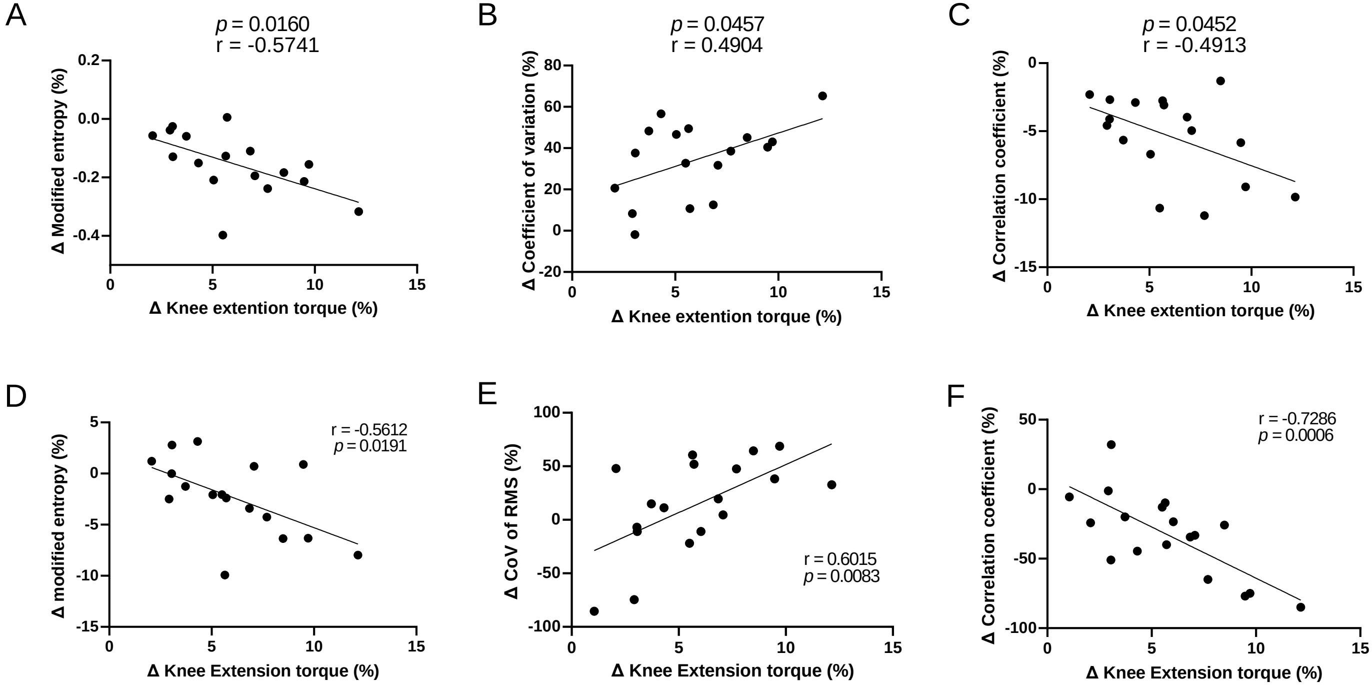
Fig. 4

Correlation coefficient between Δ knee extension torque and Δ modified entropy, Δ coefficient of variation, and Δ correlation coefficient of 50% (A–C) and 70% (D–F) maximal voluntary contraction task in the intervention group.


A
Knee extention torque (Nm)
300
250
200
150
Pre
Post
B
p < 0.0001
Knee extention torque (Nm)
300
250
200
150
Pre
Post
C
Lower limb Muscle mass (kg)
25
20
15
Pre
Post
D
Lower limb Muscle mass (kg)
25
20
15
Pre
Post


Pre
Post
Root mean square (mV)
0.25
0.20
0.15
0.10
0.05
0.00
10%
30%
50%
70%
Control group
Root mean square (mV)
0.25
0.20
0.15
0.10
0.05
0.00
*
*
10%
30%
50%
70%
Intervention group


● Control
○ Intervention
A
Modified entropy
5.80
5.82
5.84
5.86
5.88
5.90
Pre
Post
Pre
Post
10 % MVC
B
Coefficient of variation
0
5
10
15
Pre
Post
Pre
Post
10 % MVC
C
Correlation coefficient
0.92
0.94
0.96
0.98
1.00
Pre
Post
Pre
Post
10 % MVC
D
Modified entropy
5.80
5.82
5.84
5.86
5.88
5.90
Pre
Post
Pre
Post
30 % MVC
E
Coefficient of variation
0
5
10
15
Pre
Post
Pre
Post
30 % MVC
F
Correlation coefficient
0.6
0.7
0.8
0.9
1.0
1.1
Pre
Post
Pre
Post
30 % MVC
G
Modified entropy
5.82
5.84
5.86
5.88
5.90
*
Pre
Post
Pre
Post
50 % MVC
H
Coefficient of variation
0
10
20
30
*
Pre
Post
Pre
Post
50 % MVC
I
Correlation coefficient
0.85
0.90
0.95
1.00
*
Pre
Post
Pre
Post
50 % MVC
J
Modified entropy
4.5
5.0
5.5
6.0
*
Pre
Post
Pre
Post
70 % MVC
K
Coefficient of variation
0
20
40
60
*
Pre
Post
Pre
Post
70 % MVC
L
Correlation coefficient
0.0
0.5
1.0
*
Pre
Post
Pre
Post
70 % MVC


A
p = 0.0160
r = -0.5741
Δ Modified entropy (%)
0.2
0.0
-0.2
-0.4
0
5
10
15
Δ Knee extention torque (%)
B
p = 0.0457
r = 0.4904
Δ Coefficient of variation (%)
80
60
40
20
0
-20
0
5
10
15
Δ Knee extention torque (%)
C
p = 0.0452
r = -0.4913
Δ Correlation coefficient (%)
0
-5
-10
-15
0
5
10
15
Δ Knee extention torque (%)
D
r = -0.5612
p = 0.0191
Δ modified entropy (%)
5
0
-5
-10
-15
0
5
10
15
Δ Knee Extension torque (%)
E
r = 0.6015
p = 0.0083
Δ CoV of RMS (%)
100
50
0
-50
-100
0
5
10
15
Δ Knee Extension torque (%)
F
r = -0.7286
p = 0.0006
Δ Correlation coefficient (%)
50
0
-50
-100
0
5
10
15
Δ Knee Extension torque (%)