Title Page

EFFECT OF EARLY IMPLEMENTATION OF ELECTRICAL MUSCLE STIMULATION TO PREVENT MUSCLE ATROPHY AND WEAKNESS IN PATIENTS AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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ABSTRACT

Objective

Following anterior cruciate ligament (ACL) reconstruction, restricted weight bearing and immobilization results in thigh and calf muscle atrophy and weakness. The purpose of this study was to assess the effect of electrical muscle stimulation (EMS) on prevention of muscle atrophy in patients during the early rehabilitation stage after ACL reconstruction.

Methods

Twenty patients with acute ACL tears were divided into two groups randomly. The control group (CON group) participated in only the usual rehabilitation program. In addition to this protocol, the electrical muscle stimulation group (EMS group) received EMS training using the wave form of 20 Hz exponential pulse from the 2nd post-operative day to 4 weeks after the surgery.

Results

Muscle thickness of vastus lateralis and calf increased significantly 4 weeks after surgery in the EMS group, while it decreased significantly in the CON group. The decline of knee extension strength was significantly less in the EMS group than in the CON group at 4 weeks after the surgery, and the EMS group showed greater

recovery of knee extension strength at 3 months after surgery.

Conclusions

EMS implemented during the early rehabilitation stage is effective in maintaining and increasing muscle thickness and strength in the operated limb.

INTRODUCTION

Following anterior cruciate ligament (ACL) reconstruction, immobilization and restricted motion of the operated limb lead to unloading of the knee joint and restricted weight bearing for 4 weeks after surgery, resulting in atrophy and weakness of the quadriceps femoris and triceps surae muscles. Quadriceps atrophy and strength loss often exceed 20% and 30%, respectively, during the first three months following ACL reconstruction, and a 10% to 20% deficit in quadriceps size and strength can persist for years after surgery, despite concentrated rehabilitation efforts[12]. In addition, Nicholas et al. reported that ACL reconstruction resulted in a significant decrease in thigh and calf girth at 3 weeks postoperation[24]. Therefore, a primary focus of ACL rehabilitation protocols is the preservation and prompts recovery of quadriceps femoris and triceps surae force production and function. We believe it is important that patients start to exercise the quadriceps femoris and triceps surae muscles during the early post-operative period in order to prevent muscle atrophy and maintain muscle strength. One conventional choice for solving this serious problem is electrical muscle stimulation (EMS). EMS elicits skeletal muscle contractions through percutaneous electrodes that depolarize underlying motor nerves. EMS using percutaneous electrodes is noninvasive and easy-to-use. Several EMS studies have shown the potential advantages, both physiological and clinical[9, 20, 29]. These previous studies have shown that EMS can be used to mimic voluntary exercise and improve neuromuscular functions. There are other studies showing better results of voluntary training versus electrical stimulation training and that this varies depending on the type of individuals tested (healthy versus patients) [4, 5, 18, 30].

Previous studies had EMS protocols specific to each study's purpose, making it difficult to define the relationship between the EMS protocol and its effects. So it is quite difficult to prescribe a flexible EMS protocol appropriate for the desired purpose and participant's condition. Our laboratory has focused on EMS protocols, especially stimulus frequency characteristics. For example, our previous studies demonstrated in human participants that 1) training with 20 Hz frequency stimulation is more effective than 50 or 80 Hz frequency stimulations for inducing muscle hypertrophy[22], 2) EMS significantly increases glucose disposal rate (GDR) during euglycemic clamp studies[15], and a single bout of EMS to the lower extremities can significantly enhance energy consumption, carbohydrate oxidation, and whole body glucose uptake with low-intensity exercise[13], and 3) EMS induces selective fast-twitch MU activation of knee extensor muscles[14]. However, the effects of long-term EMS training using our protocol are still unknown. Further studies are necessary to test the therapeutic efficacy of our EMS device and stimulation protocol. In most studies investigating the efficacy of EMS in patients after knee surgery, the start time of the electric stimulation was often late (2-6 weeks after surgery) and the muscles had already deteriorated and lost strength[2, 6, 19, 25, 31, 32]. No one has reported the effects of EMS treatment implemented during the early rehabilitation stage for prevention of muscle atrophy in patients with ACL reconstruction. Moreover, there are no reports that evaluate changes in muscle thickness of individual muscles during EMS training.

The purpose of this study was to determine the effects of electrical muscle stimulation on the prevention of muscle atrophy in patients during the early rehabilitation stage after ACL reconstruction using a modified EMS device and stimulation protocol.

MATERIALS AND METHODS

Participants and Informed Consent

Twenty patients (16 male, 4 female), ranging in age from 13 to 54 years (26.3 ± 11.8 years) participated in this study. All patients had suffered an acute tear of the ACL, and underwent an arthroscopically assisted semitendinosus autograft reconstruction. The time from ACL tear until surgery were 3.1±1.4 months. They had no history of neuromuscular disorders except for ACL injury. Each participant provided informed consent prior to experimentation. The study protocol was approved by the Medical Ethics Committee of our hospital.

Experimental Design

Twenty consecutive patients who underwent ACL reconstruction were randomized and assigned to one of two groups: the control group (CON group) included 10 patients (8 male, 2 female, age: 29.4±14.1 years, height: 165.9±5.9 cm, weight: 60.1±10.1 kg, time from injury: 3.1±1.4 months) and the electrical muscle stimulation group (EMS group) included 10 patients (8 male, 2 female, age: 23.5±9.3 years, height: 171.0±3.9 cm, weight: 68.1±6.3 kg, time from injury: 3.1±1.4 months). There were no significant differences between the groups in age, physical characteristic, and the time from injury. The CON group received only the usual rehabilitation program determined by our institute. In addition to this standard rehabilitation protocol, the EMS group received EMS training for 4 weeks beginning on post-operative day 2. Table 1 represents the rehabilitation program determined by our institute, in which all patients in the study participated. To determine the effects of EMS, we measured muscle thickness of the rectus femoris (RF), vastus intermedius (VI), vastus lateralis (VL), and calf muscle (CA) before surgery and at 4 weeks and 3 months after surgery. We also measured changes in knee extensor muscle strength in isometric and isokinetic contractions before surgery and at 4 weeks and 3 months after surgery. Moreover, we measured lower extremity function using the Lysholm score before and at 6 months after the surgery.

EMS Training Protocol

The quadriceps femoris, hamstrings, tibialis anterior muscle, and triceps surae were selected for EMS training in this study. The EMS training was performed on the operated limb in patients of the EMS group, beginning the second day after surgery and performed 5 days per week for a period of 4 weeks. Contractions of the knee extensor, knee flexor, dorsi flexor, and plantar flexor muscles were elicited simultaneously without involving movement of the joint by percutaneous muscle stimulation for 20 minutes with the patient lying supine on a bed.

We used a specially designed handheld muscle stimulator (Homer Ion Co. LTD., Tokyo, Japan) powered by a 15-V battery for EMS training in this investigation (Fig. 1). The stimulator current waveform was designed to produce co-contractions in the lower extremity muscle groups at a frequency of 20 Hz with a pulse width of 250 μs. The duty cycle was a 5 s stimulation with a 2 s pause for a period of 20 min. Moreover, we used an exponential climbing pulse to reduce discomfort during muscle stimulation (Fig. 2). Impulses were delivered through eight silicon-rubber electrodes on the operated limb with tightly fitted shorts and leg band (Wacoal Co. LTD., Kyoto, Japan). The EMS device (Homer Ion Co. LTD., Tokyo, Japan) and specially designed stimulation shorts (Wacoal Co. LTD., Kyoto, Japan) jointly developed have been processed for its patents, and thus not yet commercially available.

All patients were treated at the highest stimulation intensity they could tolerate (peak intensity: 74–107 mA). In every training session, the stimulus intensity was individually increased as high as possible, without causing discomfort. None of the patients complained of knee pain or skin discomfort during or after EMS training, and there were no abnormal findings in periodic examinations by their attending doctors.

Muscle Thickness Analysis

Muscle thickness on the operated limb was measured using ultrasound still images (GE Yokokawa Medical Co. LTD., Tokyo, Japan) obtained using an 8.0 MHz probe with the patient lying supine or prone. Ultrasound is particularly useful because it is safe, noninvasive, and portable. Strong correlations have been reported between muscle thickness measured by B-mode ultrasound and site-matched skeletal muscle mass measured by MRI[7, 11, 21, 28, 34]. Therefore, it is plausible to use muscle thickness measurements to estimate muscle size and degree of muscle atrophy. Previous studies have shown the reliability of the ultrasound technique for measuring muscle thickness[1, 17, 26, 33]. Also, we measured the reliability of the ultrasonographic measurement in this study. The intraclass correlation coefficients in RF, VI, VL, and CA were 0.97 (0.88 – 0.99), 0.96 (0.85 – 0.99), 0.99 (0.97 – 1.0), and 0.99 (0.96 – 1.0), respectively. Muscle thicknesses of the RF and VI were measured at the level of the half distance between the anterior superior iliac spine (ASIS) and the upper pole of the patella and on the line which linked the two points. Muscle thickness of VL was measured at the level of lower one-thirds of the distance between the ASIS and the upper pole of the patella, and 3 cm lateral from the line which linked the patella to the ASIS in the supine position. Muscle thickness of CA was measured at the level of the half distance between the head of fibula and the lateral malleolus in the prone position. We measured muscle thickness with the probe placed in the transverse plane. Measurements were performed before surgery and at 4 weeks and 3 months after surgery.

Analysis of Knee Extensor Muscle Strength

We analyzed knee extensor muscle strength by measuring the maximal voluntary isometric contraction of the quadriceps femoris using the CYBEX HUMAC NORM® (Computer Sports Medicine, Inc., MA, USA.) dynamometer before surgery and at 4 weeks and 3 months after surgery. The patients were seated and stabilized in an electromechanical dynamometer with the knee flexed at 90 degrees where they attempted to maximally contract the quadriceps femoris muscles for 5 seconds while verbal encouragement from the tester and visual feedback from the dynamometer were provided. Similarly, we measured the maximal isokinetic knee extension force with an angular velocity of 60 degrees/second before surgery and at 3 months after surgery. The peak torque measured using the CYBEX HUMAC NORM® was normalized with respect to patient's body weight, which was then expressed as the percent body weight (%BW). This would allow a better understanding of the patient capacity (or muscle strength) with respect to his/or her own body weight that needs to cope with in daily life. We also calculated the ratio of changes at 4 weeks and 3 months after surgery in comparison to the pre-operation.

Analysis of Lower Extremity Function

We measured lower extremity function using the Lysholm score before and at 6 months after the surgery.

Statistics

We calculated the mean and standard error of the mean (SE) for all variables. A two-way analysis of variance (ANOVA) followed by Fisher's post-hoc test procedure was used to test differences in the effects of EMS training on dependent variables (muscle thickness and muscle strength in isometric and isokinetic contraction) before surgery and after 4 weeks and 3 months. Also we calculated the change ratio on operated side for muscle strength of knee extensor at 4 weeks and 3 months after surgery in comparison to the pre-operation, and conducted a two-way ANOVA followed by Fisher's post-hoc test procedure to test differences in effects of EMS training on dependent variables. The factors included in the two way analysis of variance were time course (pre operation, 4 weeks after surgery, and 3 months after surgery) and training group (CON group and EMS group).

RESULTS

Changes in Muscle Thickness

Fig. 3a shows RF muscle thickness of the operated side at pre-operation (PRE), 4 weeks post-operation (4WPO) and 3 months post-operation (3MPO) for both CON and EMS groups. Two-way ANOVA with Fisher's post-hoc test indicated that in the EMS group there was no significant decline in RF muscle thickness between PRE and 4WPO while the muscle thickness was significantly increased ($p=0.003$) at 3MPO. In contrast, RF muscle thickness decreased significantly ($p=0.0001$) at 4WPO compared to PRE and increased significantly ($p=0.0006$) at 3MPO compared to 4WPO in the CON group.

Fig. 3b shows the time-course changes of VI muscle thickness. There were no significant changes between PRE and 4WPO and VI muscle thickness increased significantly (p=0.007) at 3MPO compared to 4WPO in the EMS group. For the CON group, VI muscle thickness decreased significantly (p=0.0000004) at 4WPO compared to PRE and increased significantly (p=0.00001) at 3MPO compared to 4WPO, respectively.

Fig. 3c shows the time-course changes of VL muscle thickness, which increased significantly at 4WPO (p=0.0004) in the EMS group, while it decreased significantly at 4WPO (p=0.0000) but increased significantly at 3MPO (p=0.00007) compared to 4WPO in the CON group. VL muscle thickness was significantly (p=0.000003) higher at 3MPO than at PRE in the EMS group while it was significantly (p=0.017) lower at 3MPO than at PRE in the CON group.

Fig. 3d shows the time course changes of CA muscle thickness, which increased significantly at 4WPO (p=0.016) in the EMS group, while it decreased significantly at 4WPO (p=0.0002) but increased significantly at 3MPO (p=0.0002) compared to 4WPO in the CON group. CA thickness was significantly (p=0.004) higher at 3MPO than at PRE in the EMS group while we observed no significant difference between PRE and 3MPO in the CON group.

Changes in Muscle Strength

Fig. 4a shows the time-course changes of isometric knee extension strength expressed as percentage of body weight (%BW) at PRE, 4WPO and 3MPO in both groups. Isometric strength decreased significantly at 4WPO (p=0.001) and increased significantly at 3MPO (p=0.00008) in the CON group, while there were no significant changes between PRE and 4WPO and a significant increase at 3MPO (p=0.001) in the EMS group. The changes in these values are shown in Fig. 4b. Change ratios in the EMS group were significantly higher than the CON group at 4 weeks after surgery (-1.2% vs. 39.2%, p=0.008) and tended to be higher at 3 months after surgery (52.7% vs. 16.3%, p=0.072), respectively.

Change ratios in isokinetic muscle strength measured at angular velocity of 60 degrees/sec at 3 months after surgery tended to be higher in the EMS group than in the CON group (62.2% vs. 13.8%), but the difference did not reach the statistical significance.

Changes in Lower Extremity Function

Lysholm scores for the CON and EMS groups were 59.2±7.8 vs. 63.6±4.9 at pre operation, and 95.2±3.2 vs. 96.4±6.2 at 6 months after surgery, respectively. There were no significant differences in Lysholm scores between the CON and the EMS groups at 6months after the surgery.

DISCUSSION

The significant finding of this study was that 4 weeks of 20 Hz EMS training beginning in the early rehabilitation stage following ACL reconstruction prevented muscle atrophy and weakness. There have been some controversial findings regarding the effects of EMS following ACL reconstruction. Sisk et al.[31] demonstrated that there was no significant difference in strength between treatment groups, but there was a significant difference in strength between competitive and recreational athletes. Moreover, Lieber et al.[19] demonstrated that 50 Hz neuromuscular electrical stimulation and voluntary muscle contraction treatments, when performed at the same intensity, are equally effective in strengthening skeletal muscle that has been weakened by surgical repair of the ACL. On the other hand, Delito et al.[6] reported that patients in the EMS group finished a three-week training regimen with higher percentages of both extension and flexion torque when compared to patients in the voluntary exercise group. Arvidsson et al.[2] studied different parts of the quadriceps in female patients and found less atrophy of the vastus medialis after electrical stimulation. Snyder-Mackler et al.[32] reported that quadriceps strength averaged at least 70% of the strength on the uninvolved side in patients treated with high-intensity electrical stimulation (either alone or combined with low-intensity electrical stimulation), 57% in patients treated with high-level active exercise, and 51% in patients treated only with low-intensity electrical stimulation. Moreover, Fitzgerald et al.[10] reported that use of the modified EMS protocol as an adjunct to rehabilitation resulted in modest increases in quadriceps torque output after 12 weeks of rehabilitation and in self-reported knee function at 12 and 16 weeks of rehabilitation, when compared to subjects who underwent rehabilitation without EMS treatment.

Our present results confirmed significant efficacy of EMS training following ACL surgery, but differ from previous studies on some points. Our current data indicated that EMS training not only prevented muscle atrophy following ACL reconstruction, but also resulted in VL and CA hypertrophy, which have not been reported previously. We believe these different results are caused by differences in the start timing of EMS, the EMS protocol, and the electrodes.

However, there were no significant differences in Lysholm scores between the CON and the EMS groups. here were no significant differences in Lysholm scores between the CON and the EMS groups at 6months after the surgery. The non-significant difference in the Lysholm scores might have been due to the fact that the scores for the activity and knee static instability affected had already recovered for all participants by this time. On the other hand, the recovery of knee pain and swelling varied among different individuals, regardless of the way of training. For these reasons, there were no significant differences in Lysholm scores between both groups at 6 months after surgery.

Timing of EMS Treatment Initiation

The EMS program in most of the previous studies started after the affected muscles had already begun to lose strength. Delito et al.[7] started EMS within the first 6 weeks after the operation and demonstrated that the EMS group had a significantly smaller loss of isometric knee extension strength than the control group, but the treatment was not complete and was not enough to prevent muscle atrophy. Lieber et al.[19] compared EMS training with voluntary contraction training in patients 2-6 weeks after ACL reconstruction and reported equal effects of the two training protocols. In contrast, patients in our study began the EMS program on the 2nd post-operative day and were able to keep muscle strength. We succeeded in starting the EMS training just after surgery because we could train the operated limb safely without involving movement of the joint by using the EMS device to induce co-contraction of the quadriceps, hamstrings, tibialis anterior, and calf muscles.

It is unavoidable that muscle atrophy and weakness occur immediately after ACL injury. In addition, we knew that muscle atrophy and weakness following ACL reconstruction would begin immediately following surgery and that significant disuse atrophy could occur as early as the first several days after surgery because patients are forced to be non-weight-bearing and immobilized during this time. Patients are also restricted from knee extension muscle training to protect the reconstructed ligament during the early rehabilitation stage. Therefore, we believe that EMS training should start as early as possible following ACL reconstruction.

EMS Protocol

The quadriceps femoris, hamstrings, tibialis anterior muscle, and triceps surae were selected for EMS training. When EMS is used, the fatigue can be subdivided into low-frequency fatigue and high-frequency fatigue. Low-frequency fatigue is evident when the active force is depressed at frequencies that previously elicited submaximal force. Long-term low-frequency stimulation produces greater depressions of active force (called low frequency fatigue) than high-frequency stimulation in post-stimulation periods[30]. Impaired excitation-contraction coupling is responsible for low-frequency fatigue, which is prolonged and preferentially affects fast-twitch fibers[8]. High-frequency fatigue is evident when the active force is depressed at frequencies that previously elicited maximal force. High-frequency fatigue induces excessive loss of force, which can be due to electrical propagation failure with a rapid decline in the evoked action potential amplitude. Jones et al.[16] demonstrated that a reduction in extracellular [Na^+] (or accumulation of [K^+]) accelerates the rate of force fatigue in an isolated preparation, as did an increase in stimulus frequency. Moritani et al.[22] have demonstrated that significantly less force is generated after 30 seconds of high-frequency stimulation (50 Hz or 80 Hz) than after a similar period of MVC. During this period of high-frequency force fatigue, considerably greater force is generated at 20 Hz stimulation[22]. Thus, high-frequency fatigue could be largely accounted for by a failure of electrical transmission that may be due to reduced muscle membrane excitability leading to a reduction in the evoked potential amplitude and conduction time[3, 16, 22].

Most of the previous studies reported the efficacy of EMS using very high-frequency (2500 Hz) or high-frequency stimulations (50 Hz or 80 Hz)[19, 31, 32]. Eriksson et al.[9] showed that muscle enzyme activities, fiber size, and mitochondrial properties in the quadriceps femoris did not change with 50 Hz EMS training sessions over 4-5 weeks. Thus, patients in previous studies employing high-frequency (50Hz or 80Hz) EMS training might have suffered from high-frequency fatigue, so that the intended muscles were not effectively contracted. This evidence indicates that 20 Hz EMS has the potential to elicit more effective muscular improvement (a combined adaptation of neural factors and morphological changes) than high-frequency (50 Hz or 80 Hz) EMS. Our present results are in agreement with this previous evidence. Rebai et al.[25] demonstrated that twelve weeks after surgery, the quadriceps peak torque deficit in the operated limb with respect to the non-operated limb at 180 degrees/s and 240 degrees/s was significantly less in the 20 Hz group than in the 80 Hz group. Our data also suggest that low-frequency (20 Hz) EMS training is effective in muscle training. We specifically avoided the use of high frequency (50 Hz, 80 Hz, and more higher) stimulations due to “high frequency fatigue”, i.e. a reduction of muscle membrane excitability due to extracellular K+ accumulation which in turn results in force loss. In other words, high frequency stimulations reduce the time necessary to fully perform depolarization/repolarization to maintain the muscle membrane excitability. Use of high frequency EMS would reduce the pain to a greater extent, but neurologically and metabolically less effective when compared with low frequency stimulations. We have shown this phenomenon with intramuscularly recorded M-wave and force measurements[22, 23]. We have also directly measured muscle energy metabolism during low and high frequency stimulations and found that high frequency stimulations (50, 80Hz) resulted in significantly lower energy utilization due to "high frequency fatigue"[13]. Also, in our earlier preliminary studies, we have tried various stimulation protocols (20, 50, 80Hz and different duty cycle) and measured directly the rate of muscle fatigue, oxygen extraction level by near infrared spectroscopy, and mechanomyogram (MMG). We found the presently used protocol is the best in terms of avoiding fatigue accumulation without compromising muscular hypertrophy effects.

Wave Pattern and Electrodes

We used our original stimulus wave pattern and electrodes in the present study. It is generally difficult to increase stimulus intensity to the level necessary for effective muscle contraction using 20 Hz low-frequency stimulation because of skin pain or discomfort. We were able to increase the stimulus intensity higher than in previous studies without causing skin discomfort because we used an exponential climbing pulse instead of a rectangular pulse (Fig 2). Moreover, our original electrodes were large, wet-gel type electrodes that reduced source impedance so that there were no complaints of skin discomfort during or after EMS training, and no abnormal findings reported by the attending doctors. In our earlier studies[13, 15], we used square pulses without exponential climbing procedure. This stimulation technique accompanied a quite pain on the skin surface, particularly when stimulating at higher intensities. We therefore asked the EMS manufacture to invent a new stimulation procedure to reduce such discomfort as much as possible by avoiding initial sudden electrical discharge to the skin surface. A newly invented this climbing pulse stimulation procedure has been successfully adopted in the present study. This procedure includes initial phase of 10% of the final stimulus voltage and gradually reaching the final intensity with in 100 msec.

Conclusion

We were able to prevent muscle weakness in patients with ACL reconstruction by implementing our EMS protocol early in the rehabilitation stage following surgery. The decrease in the quadriceps peak torque of the operated limb was significantly less in the EMS group (1.2%) than in the CON group (39.2%) 4 weeks after surgery. The recovery ratio in the EMS group was higher than in the CON group at 3 months. We believe that the difference in muscle strength between the EMS and CON groups at 3MPO was brought about by the prevention of muscle atrophy by EMS training for 4 weeks. Consequently, we suggest that EMS training with 20 Hz exponential climbing pulse beginning immediately after surgery can prevent muscle atrophy and weakness in patients recovering from ACL reconstruction using semitendinosus autograft.

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Table 1. Rehabilitation Protocol in the Rehabilitation Unit of Kyoto University Hospital

Post-operation time	weight-bearing	ROM ex	training	cycle ergometer
2 days	NWB※1		non-oprerated leg training walking exercise on crutches muscle training around hip joint	
1 week	1/3PWB※2	0°～90°	isometric knee extention with knee flexed to 90° straight leg raise quadriceps setting exercise CKC training quarter squat (1/3PWB) CKC training calf raise (1/3PWB) bridge exercise with both legs	10 watts ×20 min
2 weeks	1/2PWB	0°～110°	knee flex exercise with weight band CKC training quarter squat (1/2PWB) CKC training calf raise (1/2PWB) bridge exercise with the operative leg	30 watts ×20 min
3 weeks	2/3PWB	0°～120°	CKC training quarter squat (2/3PWB) CKC training calf raise (2/3PWB) static squating	60 watts ×20 min
4 weeks	FWB※3	0°～130°	isokinetic muscle training of knee extension with knee flexed 60°～90° knee bent walking knee flex exercise with tube forward and side lunge balance reach leg exercise	100 watts × 20 min
5 weeks		0°～140°	long stride walking balance reach arm exercise	
6 weeks		full range	step exercise	
8 weeks			isokinetic muscles training of knee extension with knee flexed 45°～90° squat with the operative leg stand up exercise with the operative leg quadriceps setting exercise on standing	150 watts × 30 sec × 4 set
12 weeks			jogging side jump with both legs	
16 weeks			sprint run side jump with the operative leg jumping long stride walking ladder plyometric exercise	
6-8 months			return to sports	

※1 Non-Weight-Bearing ※2 Partial Weight-Bearing ※3 Full Weight-Bearing

Figure Legends

Figure 1. Patient with EMS device.

Figure 2. The illustrations of pulses (the conventional rectangular pulse and an exponential climbing pulse)

Figure 3. Time course change of muscle thickness

Figure 3a. RF muscle thickness (mm) at pre-operation (PRE), 4 weeks post-operation (4WPO) and 3 months post-operation (3MPO) for the CON and the EMS groups.

Significantly different among the evaluation times; $^{**}p<0.01$. Significantly different from the CON group; $^{\dagger\dagger}p <0.01$. Values are expressed as means ± SE (CON; n=10, EMS; n=10).

Figure 3b. VI muscle thickness (mm) at pre-operation (PRE), 4 weeks post-operation (4WPO) and 3 months post-operation (3MPO) for the CON and the

EMS groups.

Significantly different among the evaluation times; $^{**}p<0.01$. Values are expressed as means ± SE (CON n=10, EMS n=10).

Figure 3c. VL muscle thickness (mm) at PRE, 4WPO and 3MPO for the CON group and the EMS group.

Significantly different among the evaluation times; $^{**}p<0.01$. Significantly different from the CON group; $^{\dagger\dagger}p<0.01$, $^{\dagger}p<0.05$. Values are expressed as means ± SE (CON; n=10, EMS; n=10).

Figure 3d. CA muscle thickness (mm) at PRE, 4WPO and 3MPO for the CON and the EMS groups.

Significantly different among the evaluation times; $^{**}p<0.01$. Significantly different from the CON group; $^{\dagger\dagger}p<0.01$. Values are expressed as means ± SE (CON; n=10, EMS n=10).

Figure 4. Time course change of muscle strength

Figure 4a. The isometric knee extension strength on an operated side at pre-operation (PRE), 4 weeks post-operation (4WPO) and 3 months post-operation (3MPO) for the CON and the EMS groups.

Significantly different among the evaluation times; $^{**}p<0.01$. Significantly different from the CON group; $^{\dagger}p<0.05$. Values are expressed as means ± SE (CON; n=10, EMS; n=10).

Figure 4b. Changes ratios of isometric knee extension strength at 4WPO and 3MPO compared to pre-operation in both the CON and EMS groups.

Significantly different; $^{**}p<0.01$. Values are expressed as means ± SE (CON n=10, EMS n=10).

EMS Device and Tight-fitting flexible electrodes

Patient with EMS device

Stimulator

Figure 1

illustrations of pulses

rectangular pulse **exponential climbing pulse**

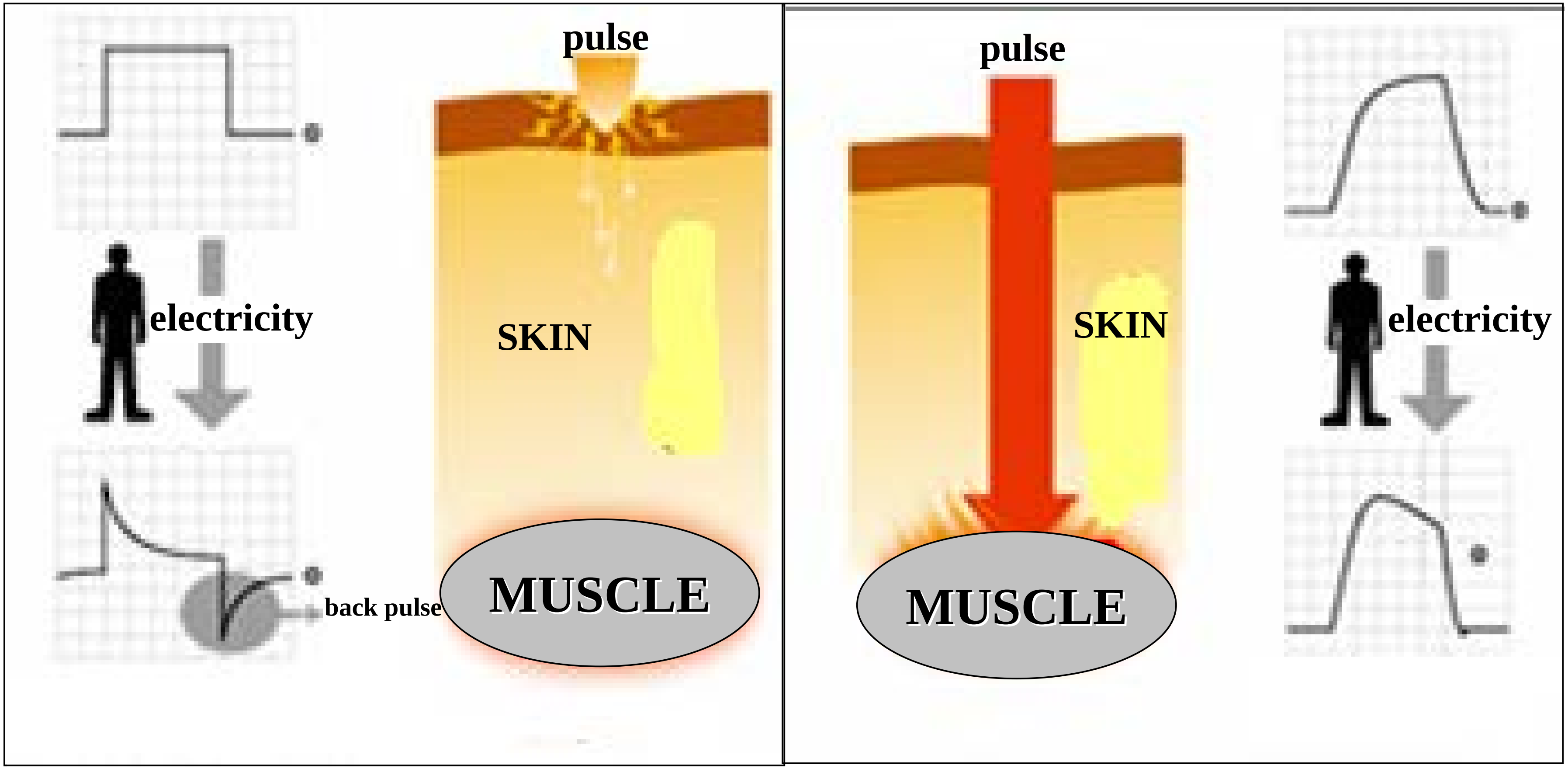


Figure 2

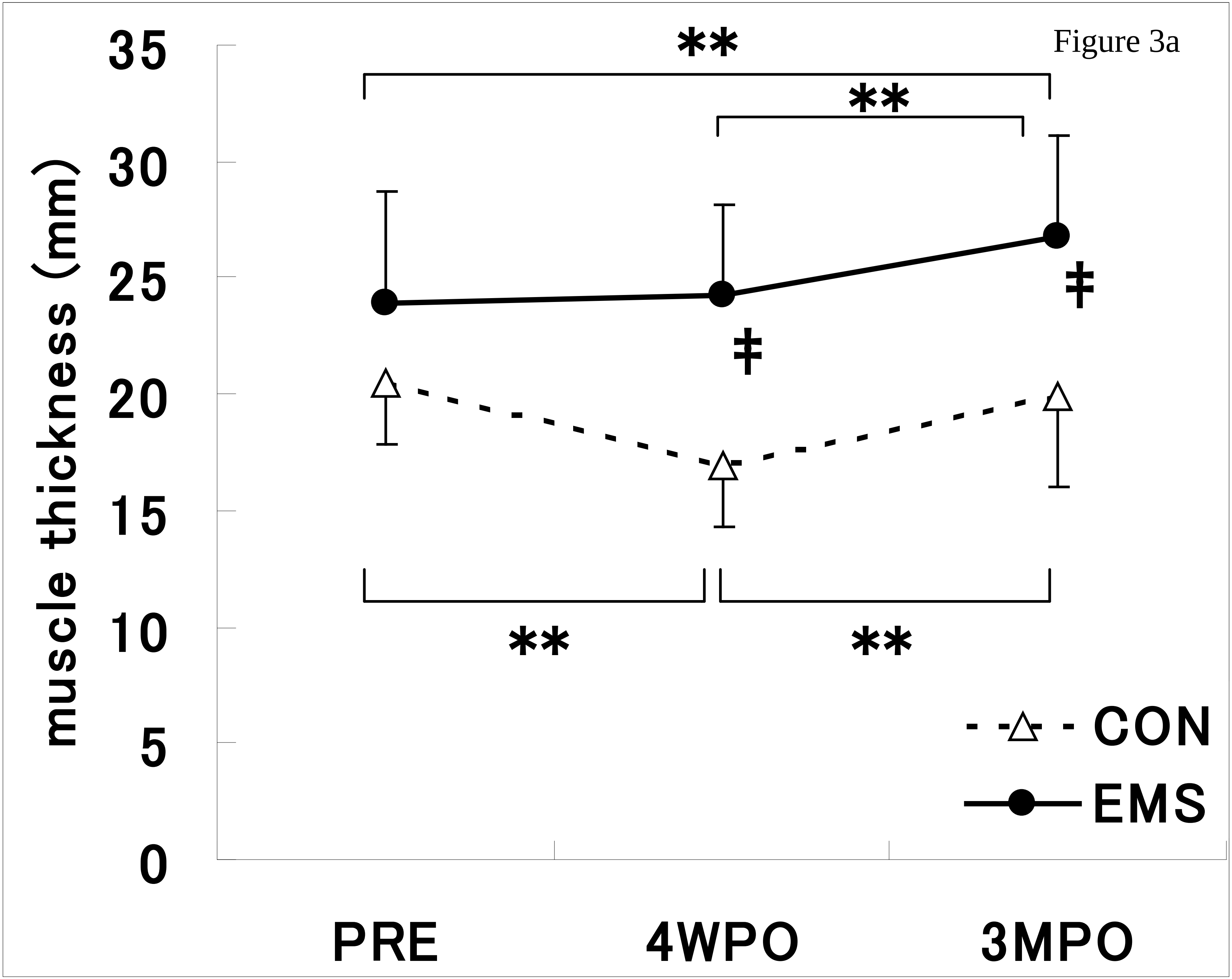
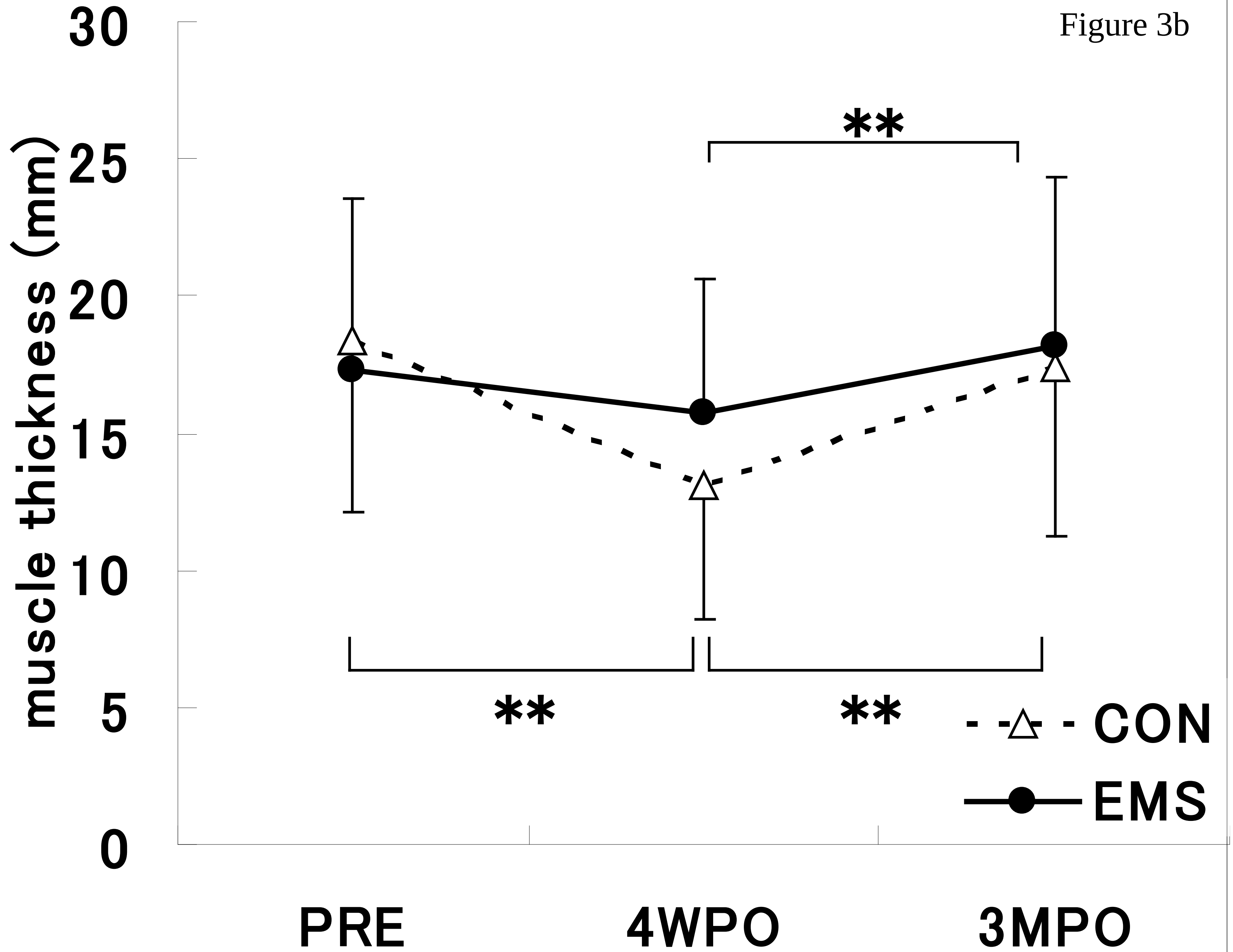


Figure 3a
muscle thickness (mm)
35
30
25
20
15
10
5
0
**
**
‡
‡
**
**
CON
EMS
PRE
4WPO
3MPO

Figure 3b



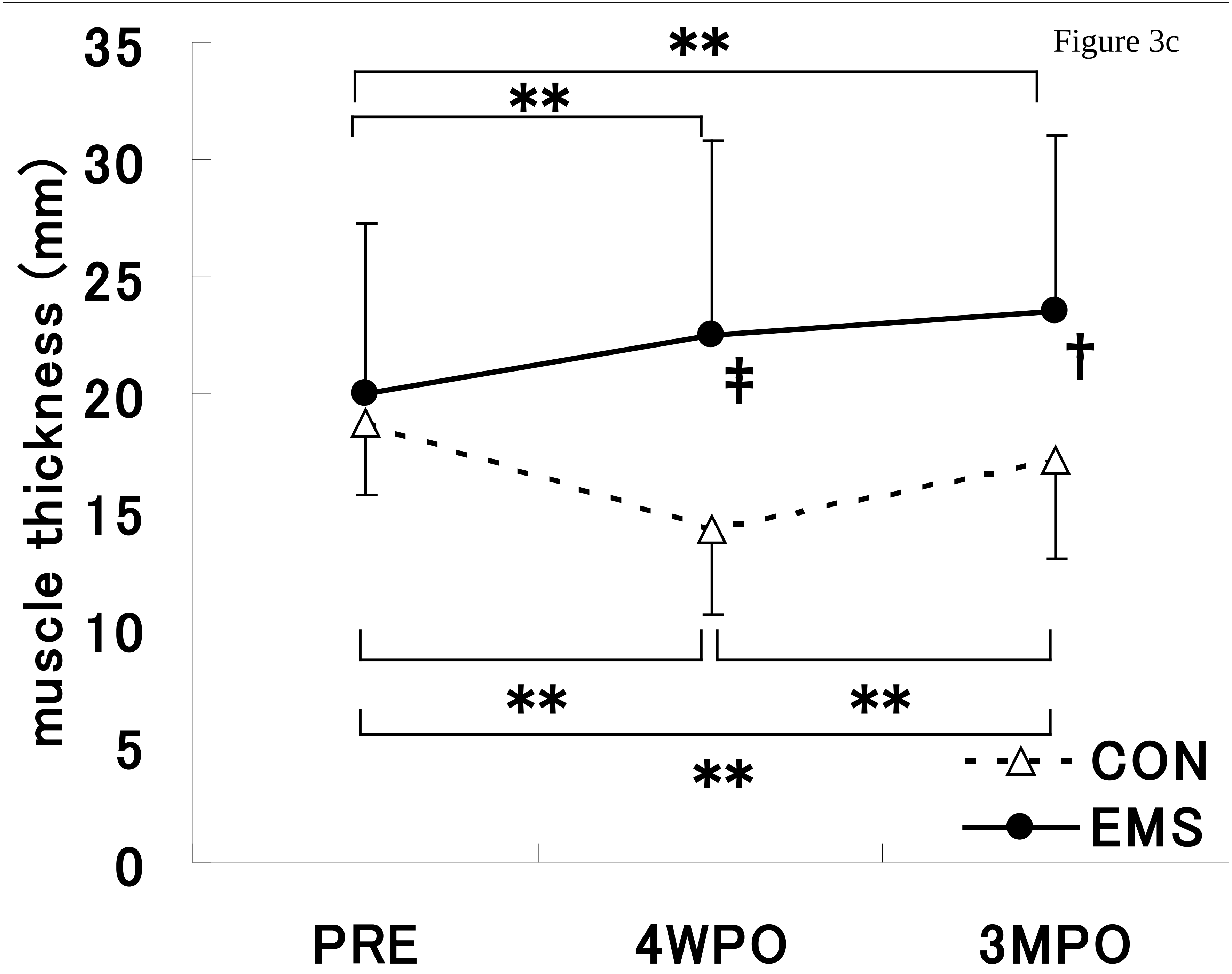


Figure 3c
muscle thickness (mm)
35
30
25
20
15
10
5
0
**
**
‡
†
**
**
**
CON
EMS
PRE
4WPO
3MPO

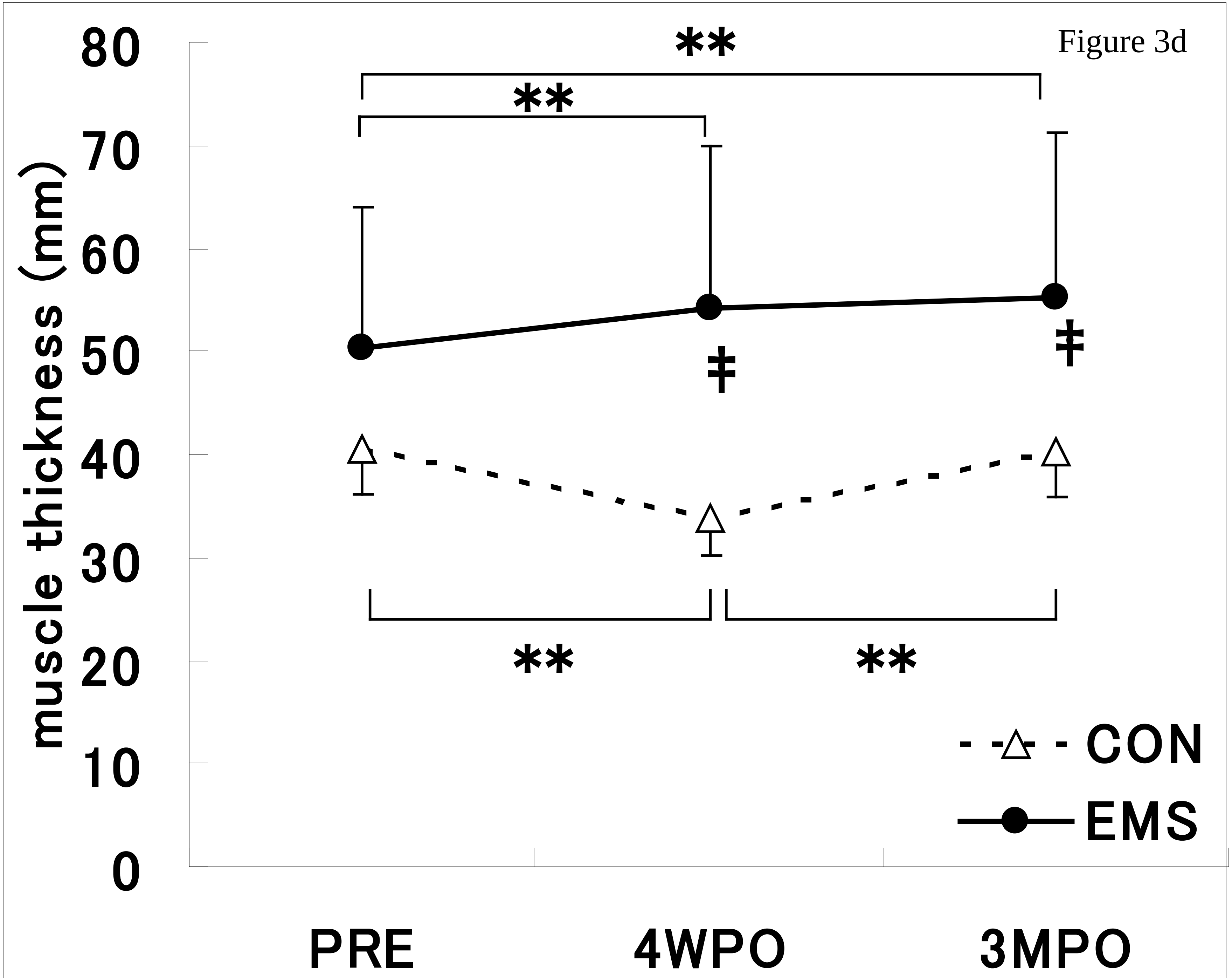


Figure 3d
muscle thickness (mm)
80
70
60
50
40
30
20
10
0
**
**
‡
‡
**
**
CON
EMS
PRE
4WPO
3MPO

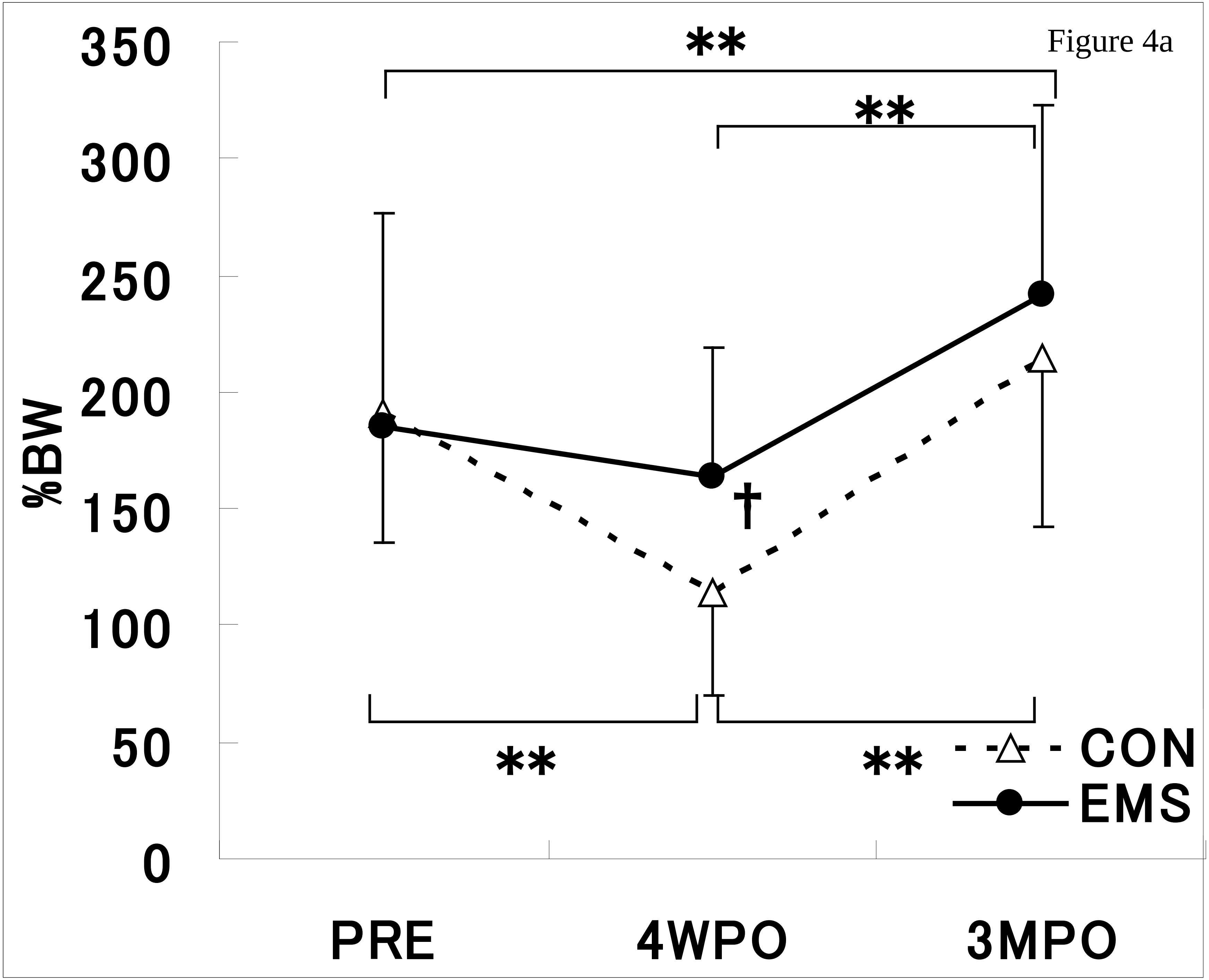
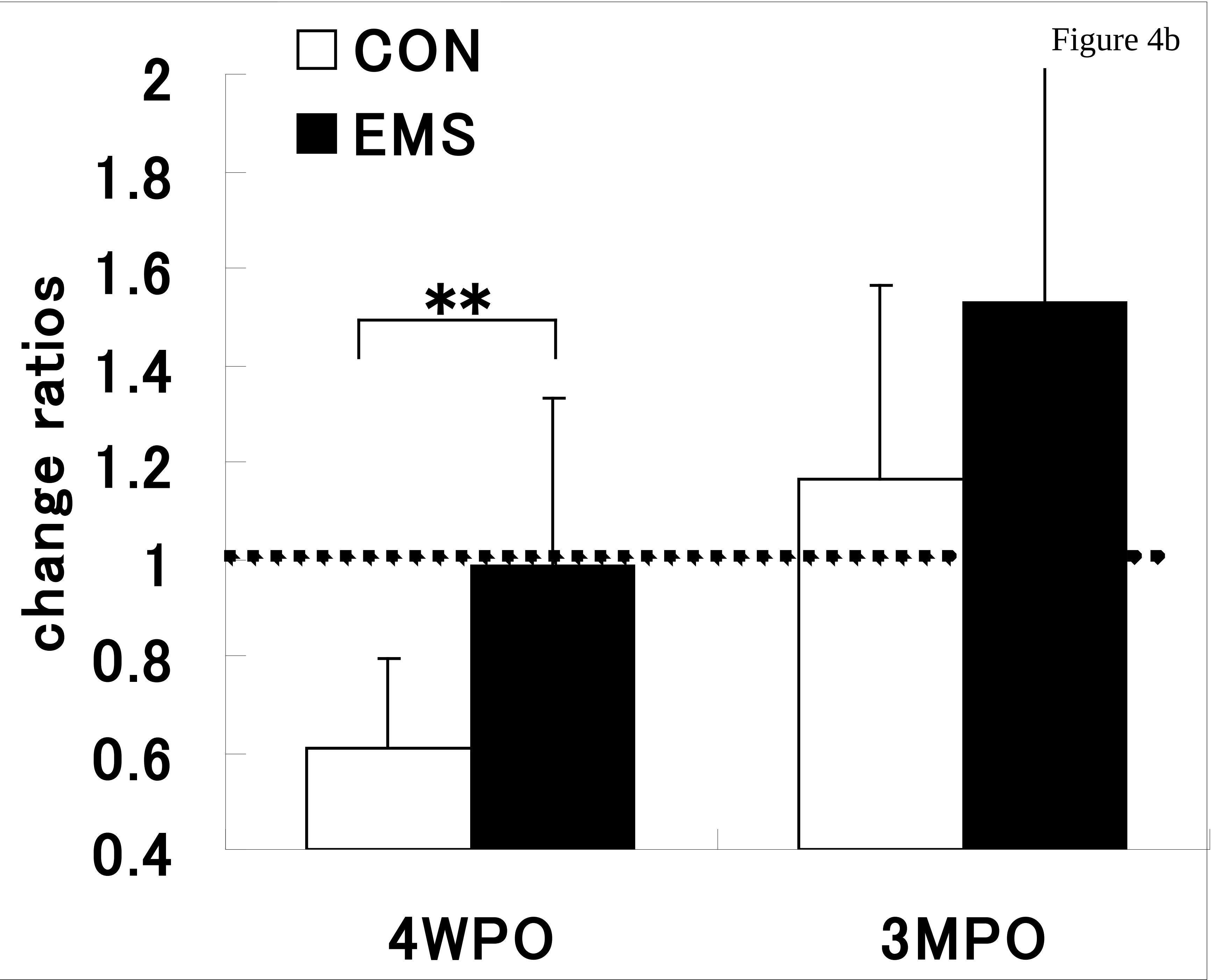


Figure 4a
350
300
250
200
150
100
50
0
%BW
**
**
†
**
**
CON
EMS
PRE
4WPO
3MPO


CON
EMS
Figure 4b
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
change ratios
**
4WPO
3MPO