Comparison between alternating and pulsed current electrical muscle stimulation for muscle and systemic acute responses

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Aldayel A, Jubeau M, McGuigan M, Nosaka K. Comparison between alternating and pulsed current electrical muscle stimulation for muscle and systemic acute responses. *J Appl Physiol* 109: 735–744, 2010. First published July 1, 2010; doi:10.1152/japplphysiol.00189.2010.—This study compared alternating current and pulsed current electrical muscle stimulation (EMS) for torque output, skin temperature (T_{sk}), blood lactate and hormonal responses, and skeletal muscle damage markers. Twelve healthy men (23–48 yr) received alternating current EMS (2.5 kHz delivered at 75 Hz, 400 μs) for the knee extensors of one leg and pulsed current (75 Hz, 400 μs) for the other leg to induce 40 isometric contractions (on-off ratio 5–15 s) at the knee joint angle of 100° (0°: full extension). The use of the legs for each condition was counterbalanced among subjects, and the two EMS bouts were separated by 2 wk. The current amplitude was consistently increased to maximally tolerable level, and the torque and perceived intensity were recorded over 40 isometric contractions. T_{sk} of the stimulated and contralateral knee extensors were measured before, during, and for 30 min after EMS. Blood lactate, growth hormone, testosterone, insulin-like growth factor 1, testosterone, and cortisol were measured before, during, and for 45 min following EMS. Muscle damage markers included maximal voluntary isometric contraction torque, muscle soreness with a 100-mm visual analog scale, and plasma creatine kinase (CK) activity, which were measured before and 1, 24, 48, 72, and 96 h after EMS. No significant differences in the torque induced during stimulation (~30% maximal voluntary isometric contraction) and perceived intensity were found, and changes in T_{sk}, blood lactate, and hormones were not significantly different between conditions. However, all of the measures showed significant ($P < 0.05$) changes from baseline values. Skeletal muscle damage was evidenced by prolonged strength loss, development of muscle soreness, and increases in plasma CK activity; however, the changes in the variables were not significantly different between conditions. It is concluded that acute effects of alternating and pulsed current EMS on the stimulated muscles are similar.

neuromuscular electrical stimulation; Russian current; skin temperature; blood lactate; muscle soreness; creatine kinase; maximal voluntary isometric contraction; growth hormone; IGF-1; testosterone; cortisol

ELECTRICAL MUSCLE STIMULATION (EMS) applies electrical current transcutaneously to muscles through electrodes to induce involuntary contractions. There are two types of currents commonly used in EMS: alternating current and pulsed current. Pulsed current EMS delivers intermittent pulses at generally 1–150 Hz (47). In contrast, alternating current EMS consists of a continuous series of alternating biphasic high-frequency pulses (e.g., 1–25 kHz) generally modulated and delivered

within the biological range, normally between 10 and 150 Hz (47). Clinical use of alternating current EMS includes pain control, spasticity management, prevention of atrophy, and edema control (46). However, it is also used in muscle training since a Russian scientist Kots advocated so called "Russian current" (2.5-kHz sinusoidal pulse stimulation) for its efficacy in increasing muscle strength in 1977 (for review see 48). Although the use of alternating current EMS has been increasing (48), pulsed current EMS is more widely used in sports training and rehabilitation, since most of the portable or battery-operated stimulators can deliver only pulsed current (24).

In alternating current EMS, the stimulus is delivered in bursts, where each burst consists of many pulses. As shown in Fig. 1, the number of bursts per second in the modulated alternating current EMS is the same as the number of pulses per second in the pulsed current EMS; however, each stimulus consists of greater number of pulses in the alternating current than the pulsed current EMS. It is possible that the distinct difference in the number of pulses delivered to muscle in stimulation produces different physiological responses between alternating and pulsed current EMS. In fact, some studies (22, 38) reported a difference in muscle force generation between alternating and pulsed current EMS. However, systematical comparisons between the two waveforms for acute muscle and systemic responses are lacking.

Snyder-Mackler et al. (37) compared the torque generation of the knee extensors among three different waveforms; 2.5-kHz alternating current and 4-kHz alternating current delivered at 50 Hz, and 50-Hz pulsed current. They reported that the torque generation was significantly lower in the 4-kHz alternating current compared with others; however, no significant difference in torque output was evident between the 2.5-kHz alternating current and the 50-Hz pulsed current. Another study compared the quadriceps fermoris torque generation during 2.5-kHz alternating current delivered at 50 Hz and 50-Hz pulsed current, and showed that the torque was significantly higher for the pulsed current than alternating current (22). In contrast, no difference was found in isometric torque of the knee extensors between 2.5-kHz alternating current delivered at 50 Hz and 30-Hz pulsed current (13) and between 2.5-kHz alternating current delivered at 95 bursts/s and 95-Hz pulsed current (15). Other studies also reported similar force generation by 2.5-kHz alternating current delivered at 75 Hz and 75-Hz pulsed current (24), or by 2.5-kHz alternating current delivered at 50 Hz and 50-Hz pulsed current (21). It does not appear that the information regarding the difference in the muscle force generation between alternating and pulsed current EMS is consistent. To the best of our knowledge, no previous study has compared the torque output between pulsed current

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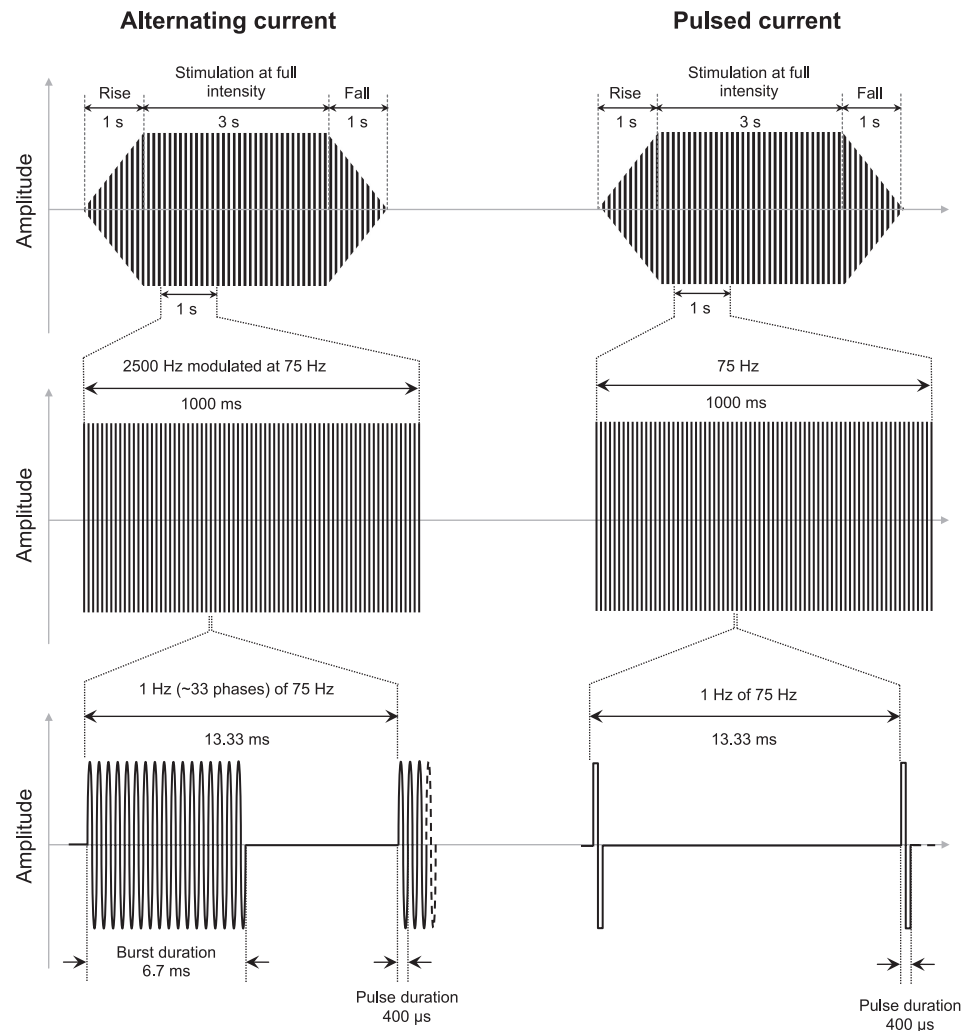
Fig. 1. Schematic diagram of alternating current and pulsed current electrical muscle stimulation (EMS) for 2 waveforms used in the present study. The alternating current was delivered at 2,500 Hz and modulated at 75 bursts/s, which results in 33 pulses in each burst, while the pulsed current was delivered at 75 Hz, and therefore only one pulse in each cycle. The pulse duration was 400 μs for both currents.

and alternating current by keeping all parameters as similar as possible except the waveform, and using the same stimulator. It is possible that a difference exists between the two current types for perceived exertion during EMS. It may be that the effect of EMS on skin temperature is associated with discomfort, and changes in skin temperature and discomfort are different between alternating current and pulsed current EMS. However, these have not been investigated in the previous studies.

Several studies have demonstrated that skeletal muscle damage is induced by isometric contractions evoked by EMS (16, 25, 28, 29). For example, Jubeau et al. (16) showed that EMS (75-Hz pulsed current) resulted in decreases in maximal voluntary isometric contraction torque, delayed onset muscle soreness (DOMS), and increases in serum creatine kinase (CK) activity. Mackey et al. (25) have reported histological damage in muscle fibers after EMS (60-Hz pulsed current). It should be noted that all of these studies used pulsed current EMS, and no previous studies have investigated skeletal muscle damage induced by alternating current EMS.

In the study by Jubeau et al. (16), they also reported that increases in blood lactate and growth hormone (GH) were significantly greater for EMS compared with the voluntary isometric contractions of the same force output. Sartorio et al. (34) compared the first and second EMS bouts (75-Hz pulsed current with pulse duration of 400 μs) consisting of 20 isometric contractions of the quadriceps femoris and showed significant increases in GH following EMS and a significant decrease in cortisol at 60 min after the first EMS. To understand the effect of EMS on hormonal responses better, other anabolic hormones (e.g., testosterone, IGF-1) that are often investigated in resistance exercise (19) should be investigated. No previous study has compared alternating current and pulsed current EMS for changes in hormones (GH, testosterone, IGF-1, and cortisol) and blood lactate.

Therefore, the purpose of this study was to compare alternating current and pulsed current during a typical EMS strength training session (20, 45) for torque generation, perception and skin temperature, symptoms of skeletal muscle damage, and hormonal responses. To compare pulsed current and alternating EMS, the present study set the stimulation parameters similarly between the two stimulation conditions. Based on the previous studies (12, 27, 40), 75 Hz was chosen for the frequency of the pulsed current EMS, and 2.5 kHz was chosen for alternating current (32, 36, 37). It was hypothesized that significant differences would be evident between alternating and pulsed current EMS for torque output, skin temperature, skeletal muscle damage, and hormonal responses.

METHODS

Study Design

Twelve volunteers participated in two EMS sessions separated by 2 wk: one for pulsed current session and the other for alternating current session in a randomized, counterbalanced order. The 2-wk interval between bouts was set to provide a time for elevated plasma CK activity after the first EMS session to return to baseline value. The subjects did not receive any information which current they were receiving in the EMS sessions. A familiarization session was conducted before the study, which included maximal voluntary isometric contraction strength (MVC) measures at different knee joint angles (40°, 70°, 100°), and EMS that included three to five electrically evoked isometric contractions at submaximal intensity. For each EMS session, the subjects were asked to report to the laboratory for 6 days: baseline measure session held 1–3 days before EMS session, EMS session day, and 4 consecutive days following the EMS session (Fig. 2). Forty isometric contractions of the knee extensors of one leg were evoked in each EMS exercise, and one leg received pulsed current EMS, and the other leg had alternating current EMS. Both EMS sessions were performed at the same time of the day for each subject between 8 AM and 10 AM to eliminate the effects of possible diurnal variations on hormonal responses and other measures. The independent variable in this study was the waveform used in EMS (alternating current vs. pulsed current), and the dependent variables consisted of knee extensors' torque and rate of perceived exertion during EMS, skin temperature, blood lactate concentration, growth hormone, testosterone, IGF-1, and cortisol concentrations, and indirect markers of muscle damage such as MVC of the knee extensors, muscle soreness, pressure pain threshold, and plasma CK activity. The study was approved by the Edith Cowan University Human Research Ethics Committee.

Subjects

Twelve healthy men (mean ± SD age: 31.2 ± 5.5 yr, body mass: 81.4 ± 15.2 kg, height: 174.3 ± 4.8 cm), who had not been involved in resistance training program for at least 6 mo before the study and not had an injury in their knee joints, participated in this study after signing the informed consent form. During the experimental period, subjects were asked not to change their diet habits and not to take any medicines nor have any interventions other than those given in the study. Subjects were requested to avoid consuming caffeine and alcohol 1 day before the EMS session and not to undertake any physical activity during the experimental period. Female subjects were excluded to avoid possible sex difference in hormonal responses (4, 18, 51) and muscle damage (6, 43), and to make the variability of

the criterion measures as small as possible to increase the statistical power.

EMS

Each subject seated on a Biodex isokinetic dynamometer chair (Biodex Medical Systems) with his knee joint angle of 100° (0° corresponding to the full extension) and the trunk angle of 110°. Straps secured the pelvis and chest to minimize the movements of the hip and trunk during contractions. An Intelect Advanced Colour Stim (Chattanooga Group, TN) was used to stimulate the quadriceps femoris muscles. Four self-adhesive electrodes were placed on the anterior surface of one thigh as follows: two positive electrodes (50 × 50 mm) over the motor point of the vastus lateralis and vastus medialis muscles, and two negative electrodes (50 × 100 mm) placed on the proximal portion of the quadriceps femoris muscle based on a previous study (16). The placement of electrodes was similar between the two EMS sessions.

As shown in Fig. 1, the waveform of pulsed current was biphasic symmetrical rectangular, and balanced stimulus pulses were delivered with frequency of 75 Hz and pulse duration of 400 μs (26, 41). The EMS parameters for alternating current were adjusted at 2.5-kHz alternating sinusoidal current (pulse duration = 400 μs) and delivered in bursts with a carrier frequency of 75 Hz and the bursts duration of 6.5 ms based on previous studies (24, 33, 48). The other stimulation parameters were the same between the alternating and pulsed current EMS (Table 1). For both currents, the ratio was 5 s stimulus on time and 15 s stimulus off time, so the duty cycle time was 25%. The ramping time was included in the stimulation time (on-time) such as 1 s for the rise time and 1 s for the fall time. Current intensity started from 0 mA and was increased rapidly to muscle contraction threshold of each subject every four to five contractions by a 3- to 6-mA increment (Fig. 3A). The settings were to achieve the maximum possible force output of each subject in the EMS. The EMS session consisted of a total of 45 isometric contractions of the extensor muscles for 15 min; however, only the last 40 contractions were used for further analysis, since the intensity of the first five contractions was generally very low. The isometric torque of each contraction was recorded by the isokinetic dynamometer.

Dependent Variables

Knee flexion torque during EMS. Each contraction torque induced by EMS was measured and recorded over 40 isometric contractions using a Biodex isokinetic dynamometer software and saved for later analysis to determine torque (peak torque, average torque) and torque time integral of each contraction. The average torque during the EMS-evoked contraction excluding the ramp time and torque time

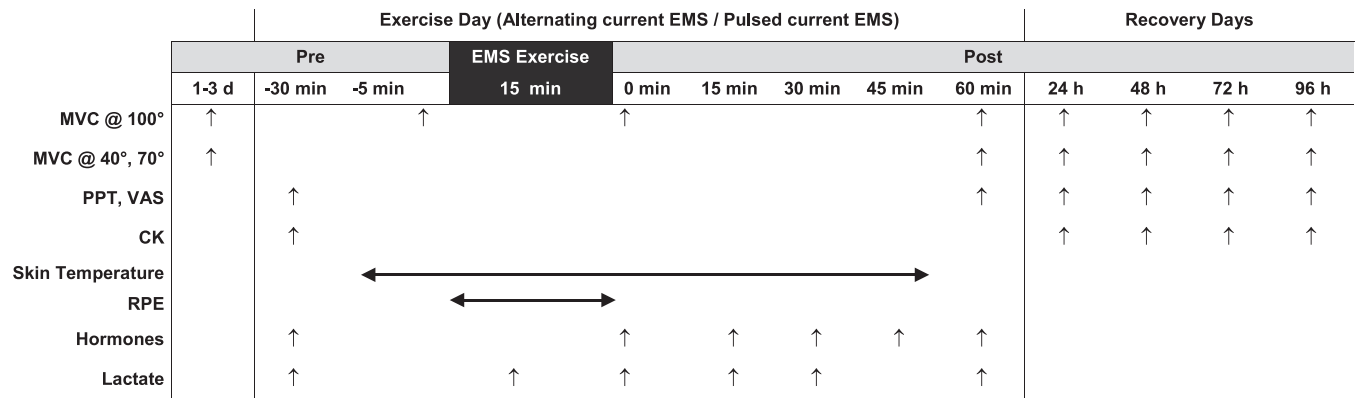|	Exercise Day (Alternating current EMS / Pulsed current EMS)									Recovery Days			
	Pre			**EMS Exercise**	**Post**								
	1-3 d	-30 min	-5 min	15 min	0 min	15 min	30 min	45 min	60 min	24 h	48 h	72 h	96 h
MVC @ 100°	↑		↑		↑				↑	↑	↑	↑	↑
MVC @ 40°, 70°	↑								↑	↑	↑	↑	↑
PPT, VAS		↑							↑	↑	↑	↑	↑
CK		↑								↑	↑	↑	↑
Skin Temperature				←————————————————————————————→									
RPE				←——————→									
Hormones		↑			↑	↑	↑	↑	↑				
Lactate		↑		↑	↑	↑	↑	↑					

Fig. 2. Diagram showing the measurement time line. MVC, maximal voluntary contraction at different knee joint angles (40°, 70° and 100°); PPT, pressure pain threshold; VAS, visual analog scale for muscle soreness assessment; CK, plasma creatine kinase activity; RPE, rating of perceived exertion.

Table 1. *Stimulation parameters for alternating current and pulsed current electrical muscle stimulation*

	AC	PC
Pulse frequency	2.5 kHz delivered at 75 Hz	75 Hz
Pulse duration	400 μs	400 μs
Burst duration	6.7 ms	Not applicable
Stimulus on time	5 s (rise time 1 s/fall time 1 s)	5 s (rise time 1 s/fall time 1 s)
Stimulus off time	15 s	15 s
Cycle time	13.3 ms	13.3 ms
Duty cycle (on-off time)	25 % (5 s /15 s)	25 % (5 s/15 s)
Pulse duty cycle	Not applicable	3 %
Burst duty cycle	50 %	Not applicable
Waveform	Alternating sinusoidal	Biphasic, symmetrical rectangular
Stimulus intensity	Maximal tolerance	Maximal tolerance

AC, alternating current; PC, pulsed current.

integral of each contraction were calculated using Chart data analysis software (ADInstruments, Bella Vista, Australia).

Rating of perceived exertion. The rating of perceived exertion (RPE) during the EMS was assessed by a Borg's standard 6–20 scale at every six contractions.

Skin temperature. Skin temperature (T_{sk}) was recorded continuously before, during, and for 30 min after EMS. Four skin thermistors (YSI Temperature, 400 series; Dayton, OH) were placed on the skin using fixomull tape near the positive electrodes (vastus medialis and vastus lateralis), mid thigh of the stimulated leg, and the mid thigh of nonstimulated leg. Temperature was recorded by a data-logger set (Squirrel SQ series, Grant Instruments) at 1 Hz with 1-min intervals starting from 5 min preexercise to 15 min post-EMS. The temperature was obtained at 5-min intervals from the recorded data for further analysis.

Blood lactate concentration. A 5-μl sample of blood was obtained by finger prick and loaded to a test strip of Lactate Pro Analyzer (Arkray, Kyoto, Japan) to determine lactate concentration. The measurement was taken before, during the middle of EMS session (after the 20th contraction), and immediately after and 15, 30, and 60 min post-EMS exercise.

Serum hormone concentration. A 21-gauge Teflon cannula (Becton Dickinson, Franklin Lakes, NJ) was inserted to a superficial forearm vein, and an extension tube fitted with a two-way stopcock was attached to the cannula. Blood samples were obtained into disposable syringes before, immediately after, and 15, 30, 45, and 60 min following EMS and put into plain 3-ml Vacutainer tubes (Becton Dickinson). The tubes were left at room temperature for 20 min to clot and centrifuged at 3,000 rpm for 10 min at 4°C. The serum samples were frozen and stored at −80°C for later analyses of growth hormone (GH), total testosterone, cortisol, and IGF-1 using enzyme-linked immunosorbent assay with test kits (GH: DSL-10–1900; total testosterone: DSL-10–4000, cortisol: DSL-10–2000, IGF-1: DSL-10–9400, Diagnostic Systems Laboratories, Webster, TX). Each sample was duplicated in the measures, and the average value of the two values was used for further analysis. The hormone concentrations were determined using a multilabel counter set to 450 nm (VersaMax, Molecular Devices, Sunnyville, CA). The coefficient of variation (CV) for GH, total testosterone, cortisol, and IGF-1 in the present study were 6.5, 4.8, 8.0, and 8.8%, respectively.

Maximal voluntary isometric contraction torque. Subjects sat on the Biodex isokinetic dynamometer's chair in the same setting as the EMS protocol, the rotation axis of the knee of the tested leg was aligned with the rotation axis of the dynamometer's armature, and the ankle cuff was joined ~1 cm proximal to the medial malleolus. Gravity corrections were made at 10° of knee flexion. Subjects were asked to keep both arms positioned across the chest with each hand clasping the opposite shoulder. MVC was measured at three different knee joint angles, 40°, 70°, and 100°, at 1–3 days before and 1, 24, 48, 72, and 96 h after EMS exercise. At immediately before and after EMS exercise, MVC was assessed at 100° only to minimize the influence of maximal voluntary isometric contractions on hormones, and the angle (100°) was chosen because it was the angle that the isometric contractions were evoked by EMS. No significant difference in MVC measured at 100° was found between the measures taken 1–3 days before and immediately before the EMS exercise. The reliability of the MVC measure at 100° indicated by CV based on the two baseline measures taken 1–3 days before and immediately before the EMS session was 5.8%. Three maximal voluntary isometric contractions for 3 s with a 30-s rest between attempts were performed for each angle, and a 60-s rest was given between different angles. Strong verbal encouragement was given to the subjects during each trial. The peak torque from three contractions for each angle was used for later analysis. The stimulated leg was always measured first followed by the control leg, and the time lag between the legs was ~10 min.

Muscle soreness. Subjects were asked to rate their pain of the knee extensors on a 100-mm visual analog scale (VAS) with 0 representing "no pain" and 100 as "unbearable pain" while the subjects were asked to squat. Subjects were asked to stand with their legs shoulder width apart and bent each knee slowly to a 90° angle, then returned to the initial position.

Pressure pain threshold. Pressure pain threshold (PPT) was assessed using an electronic algometer (Type II, Somedic Production AB, Sollentuna, Sweden). The algometer was calibrated for each occasion, and the same investigator took all measurements. The probe head (surface area = 1.0 cm^2) of the algometer was placed perpendicular to four sites of the quadriceps femoris muscle used for the palpation soreness measures that were clearly marked by a water-proof ink pen. Force was gradually applied at a constant rate of 50–60 kPa/s until the subject reported the first feeling of noticeable pain. Three measurements were taken from each site sequentially with a minimum of 30-s interval and 1 min between different sites (23) in the following order: the middle point of the rectus femoris, the proximal points of rectus femoris, vastus medialis, and vastus lateralis. The value in kilopascals (kPa) corresponding to the amount of force applied was recorded. The mean of the three measurements for each site was used for further analysis, and the values of all sites were averaged to assess the tenderness in quadriceps muscle.

Plasma CK activity. Blood samples for CK were taken from a fingertip using a heparinized capillary (30 μl) and loaded onto a test strip. CK activity was assessed using a Reflotron spectrophotometer (Boehringer-Mannheim, Pode, Czech Republic) in duplicate, and if the difference of the two values was greater than 10%, additional measurements were taken. In this method, the normal reference ranges for adult men are 20–220 IU/l according to the instruction sheet of the test kit (Reflotron CK, Roche Diagnostics).
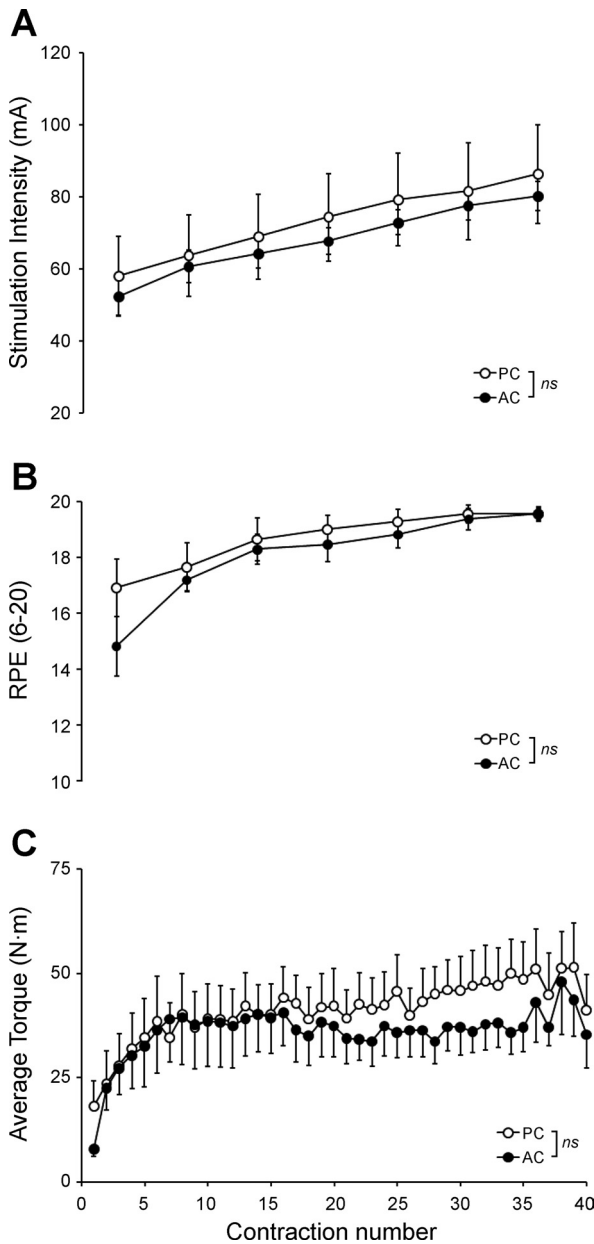
A

B

C

Fig. 3. Changes in stimulation intensity (*A*), RPE (*B*), and peak torque (*C*) over 40 isometric contractions during alternating current (AC) and pulsed current (PC) EMS. ns, no significant difference between currents for the changes over time.

Statistical Analysis

Changes in stimulation intensity (amplitude), RPE, and torque over 40 contractions and T_{sk}, blood lactate, and hormones before, during, and after EMS were compared between the current and pulsed EMS using a two-way repeated-measures ANOVA. A two-way repeated-measures ANOVA also compared the changes in MVC, VAS of muscle soreness, pressure pain threshold, and plasma CK activity before and after EMS between the two stimulation conditions. When the ANOVA showed a significant interaction effect, a Tukey's post hoc test was followed to compare between the stimulation conditions for each time point. The statistical analyses were performed using a Statistical Package for Social Sciences (version 18.0; SPSS). All data are expressed as means ± SD, and a significance level was set at $P < 0.05$.

RESULTS

Stimulation Intensity, RPE, and Torque Generated During EMS

Changes in stimulation intensity (Fig. 3*A*) and RPE (Fig. 3*B*) over 40 contractions are not significantly different between the alternating and pulsed EMS. Stimulation intensity gradually increased throughout the EMS for both currents similarly. RPE increased in the first 20 contractions and reached to a nearly maximum value after the 25th contraction, without a significant difference between the waveforms. As shown in Fig. 3*C*, no significant difference between the waveforms was evident for the torque output over 40 contractions. The torque increased in the first 10–15 contractions in both currents, but no further increases were seen after that despite the increases in the intensity. The averaged torque evoked by EMS was 54 ± 24 N·m for alternating current and 62 ± 28 N·m for pulsed current with no significant difference between the currents. The level of the torque output during EMS relative to the MVC at 100° was 28.4 ± 4.4% for the alternating current EMS and 31.8 ± 3.7% for the pulsed current EMS, without significant difference between the waveforms.

Skin Temperature

Changes in T_{sk} were similar among the three sites on the stimulated leg; thus the data of the midthigh of the simulated leg are shown in Fig. 4. It also includes T_{sk} of the midthigh of the nonstimulated leg. T_{sk} increased significantly from the baseline after 10 min of EMS for the stimulated leg while the control leg showed significant decreases. No significant difference was evident between the waveforms.

Blood Lactate and Hormones

Table 2 shows changes in blood lactate and serum hormone concentrations. Blood lactate increased significantly during and immediately after EMS and returned to baseline values within 15 min postexercise. No significant difference in the changes in blood lactate concentration over time was evident
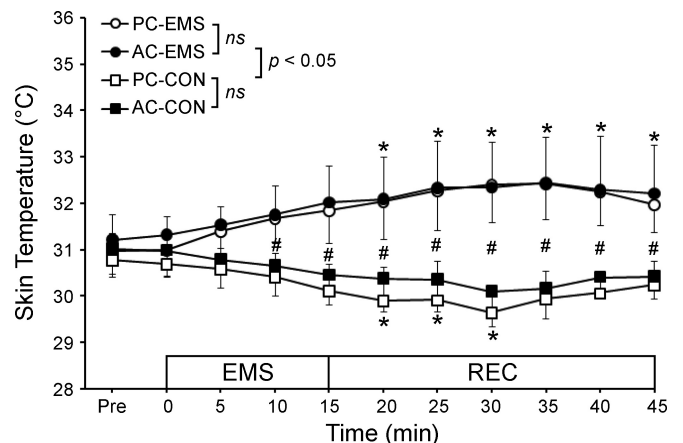

Fig. 4. Changes in skin temperature of the electrically stimulated (EMS) and control (CON) leg before (Pre), during (EMS), and for 30 min after EMS (REC) for alternating current (AC) and pulsed current (PC) electrical stimulation. ns, no significant difference between currents for the changes over time. *Significant ($P < 0.05$) change from baseline. #Significant ($P < 0.05$) difference between legs.

Table 2. *Changes in blood lactate, and serum GH, testosterone, IGF-1, and cortisol concentrations before (Pre), in the middle of electrical muscle stimulation after 20th contraction (EMS), immediately after (0), and 15, 30, 45 and 60 min following alternating current and pulsed current electrical muscle stimulation*

Hormones	Current	Pre	EMS	0 min	15 min	30 min	45 min	60 min
Lactate, mmol/l	AC	1.5 ± 0.1	2.1 ± 0.1*	2.9 ± 0.2*	1.7 ± 0.2	1.4 ± 0.1	-	1.1 ± 0.1
	PC	1.8 ± 0.1	2.6 ± 0.2*	3.4 ± 0.3*	1.7 ± 0.1	1.5 ± 0.1	-	1.3 ± 0.1
GH, ng/ml	AC	0.8 ± 0.3		3.1 ± 1.0*	3.5 ± 0.8*	2.9 ± 0.7*	2.3 ± 0.5	1.8 ± 0.4
	PC	0.8 ± 0.2		2.3 ± 0.7	3.1 ± 0.7*	2.5 ± 0.7*	1.9 ± 0.5	1.4 ± 0.4
Testosterone, pg/ml	AC	19.8 ± 1.6		28.2 ± 3.9*	28.1 ± 3.0*	27.5 ± 2.8*	25.8 ± 2.4	21.3 ± 2.3
	PC	18.4 ± 1.9		28.4 ± 3.6*	28.5 ± 2.9*	26.1 ± 3.5	23.3 ± 2.5	19.7 ± 2.1
IGF-1, nmol/l	AC	34.4 ± 3.9		33.3 ± 5.7	32.1 ± 4.7	31.2 ± 3.4	32.8 ± 3.5	28.9 ± 3.6
	PC	31.8 ± 4.8		32.9 ± 4.8	33.2 ± 6.3	33.6 ± 4.7	34.4 ± 5.2	32.5 ± 5.9
Cortisol, nmol/l	AC	658.3 ± 28.4		614.6 ± 29.5	599.6 ± 37.5	592.7 ± 46.4	542.8 ± 43.8*	562.1 ± 5.8*
	PC	692.3 ± 26.4		659.6 ± 30.3	631.6 ± 33.9	591.1 ± 41.7	553.8 ± 44.5*	575.2 ± 5.2*

Values are mean changes ± SD. GH, growth hormone. *Significantly different from Pre value.

between pulsed current and alternating current. No significant differences in the changes in any hormones were evident between the waveforms. Serum GH increased more than 400% after EMS and peaked at 15 min postexercise in both currents. Serum testosterone also significantly increased ~150% immediately and 15 min after EMS. Serum cortisol decreased significantly from baseline to 60 min post-EMS. Serum IGF-1 did not change significantly over time.

Muscle Damage Markers

MVC was not significantly different between currents before EMS for both legs for all angles (Fig. 5). The MVC of the control leg did not change significantly over time following EMS. MVC decreased significantly below the baseline immediately after alternating current EMS and pulsed current EMS by 23.1 ± 4.2% and 26.1 ± 2.8%, respectively, without significant difference between the waveforms. No significant differences in the recovery of MVC were evident between the alternating and pulsed current EMS for all angles. The recovery of MVC at 40° and 70° was significantly faster than that at 100° and returned to the baseline values within 24 h; however, MVC at 100° remained lower than baseline for all time points following EMS.

Muscle soreness peaked 48 h post-EMS for both currents (Fig. 6A), and no significant differences in muscle soreness were evident between the waveforms. The four locations of PPT measurements showed similar values, and the changes were not significantly different among the sites; thus changes

in the mean PPT value of the four sites are shown in Fig. 6B. A decrease in PPT indicates that muscles became more tender after EMS, but no significant difference between the conditions was found. Plasma CK increased significantly after both currents, and peak value was 1,262 ± 339 IU/l for alternating current, and 1,677 ± 491 IU/l for pulsed current, without significant difference in the changes between the two conditions (Fig. 6C).

DISCUSSION

The present study showed that no significant differences existed between the alternating current and pulsed current for *1*) torque generation and RPE during EMS, *2*) changes in skin temperature, blood lactate, and hormones before, during, and after EMS, and *3*) changes in markers of muscle damage following EMS. Additionally, this is the first study to report that testosterone increases but IGF-1 does not change significantly during and after EMS.

Our data support the previous studies (13, 15, 21, 24, 37) reporting that isometric force generation during EMS was similar between alternating and pulsed currents, in which an equivalent number of stimuli per second was delivered for both currents, although the number of pulses in a stimulus was different. In the present study, the currents were delivered at 75 Hz for both stimulation conditions, either bursts per second (alternating current) or pulses per second (pulsed current), and the muscles were stimulated at maximally tolerable level for both conditions (Fig. 1). The other stimulation parameters were
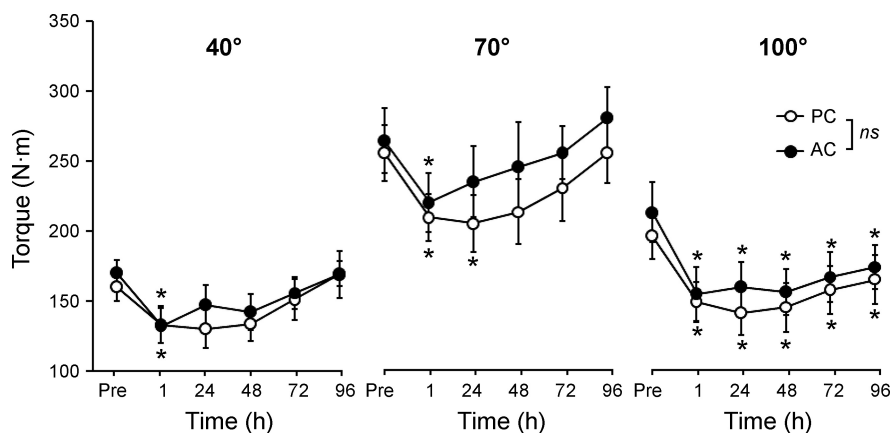

Fig. 5. Changes in MVC torque at 40°, 70°, and 100° before (Pre), and 1, 24, 48, 72, and 96 h after alternating current (AC) and pulsed current (PC) electrical stimulation. ns, no significant difference between currents for the changes over time. *Significant ($P < 0.05$) difference from the baseline.
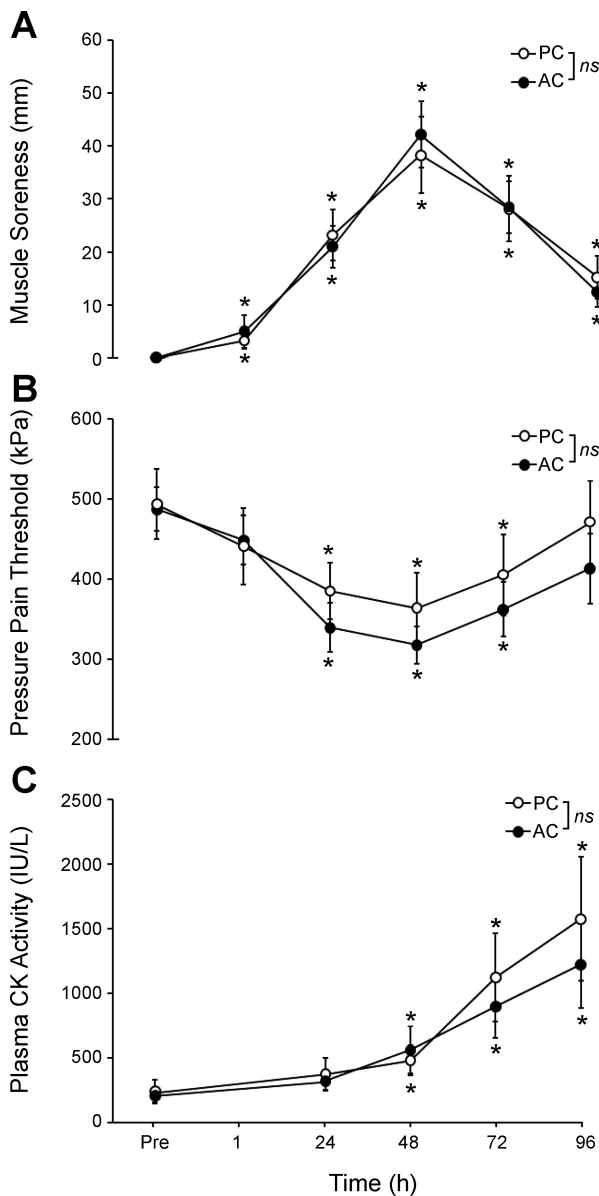
Fig. 6. Changes in muscle soreness (VAS) on squat (*A*), PPT (*B*), and plasma CK activity (*C*) before (Pre), and 1–96 h after alternating current (AC) and pulsed current (PC) electrical muscle stimulation. ns, no significant difference between currents for the changes over time. *Significant ($P < 0.05$) difference from baseline value.

the same between the conditions (Table 1), and no significant difference in the stimulation amplitude was evident between the alternating and pulsed current EMS (Fig. 3*A*). It seems that the number of stimuli per second determines the force generation (75 stimuli in the present study) rather than the number of pulses in each stimulus (33 stimuli for alternating current, and 1 stimulus for pulsed current in the present study). Thus the additional pulses in the alternating current EMS do not appear to contribute to the force generation (21). Several studies have reported that greater muscle fatigue is induced during alternating current than pulsed current EMS (21, 22, 24, 38). Although the peak torque generated during EMS was not significantly different between alternating current EMS and pulsed current EMS (Fig. 3*C*), the present study also found that the torque output

during alternating current EMS was not as stable as that during pulsed current EMS as reported in previous studies (13, 38).

The torque output increased to the level of ~30% MVC in the first 15 contractions and no further increases were seen afterward for both waveforms (Fig. 3*C*), despite the consistent increases in the stimulation intensity (Fig. 3*A*). The level of torque output in the present study (~30% of MVC) was similar to that of a previous study (16) in which the same electrode placement and stimulation parameters (e.g., 75 Hz, pulse duration 400 μs) as those of the present study were used. The plateau of maximal torque despite the increases in stimulation intensity (Fig. 3*A*) would indicate that no further increases in motor unit recruitment were made. It appears that muscle fatigue occurs at central and/or peripheral origins during EMS (3), which prevented further increases in force generation. It is possible that the high-frequency stimulation (75 Hz) impaired muscle excitation (7). Additionally, the plateau might be due to muscle damage, where a structural damage to the force-bearing elements and/or a failure of the excitation-contraction coupling occurred (49).

The nonlinear increases in RPE appear to indicate an increase in subjects' tolerance to EMS, probably due to an increase in threshold of pain receptors (31). Two previous studies reported that the level of discomfort or pain during stimulation was similar between alternating current and pulsed current EMS (13, 24). For example, Grimby and Wigerstad-Lossing (13) reported that discomfort of the quadriceps muscle stimulated at maximally tolerable intensity was similar between alternating and pulsed current using a Borg's scale. Lyons et al. (24) also showed no significant difference in discomfort between alternating current EMS and pulsed current EMS using a numeric pain rating scale. Since the stimulation intensity was set at the maximum tolerance of each subject in the present study, the similar RPE between the conditions seems reasonable. Thus neither of alternating current or pulsed current can be preferably chosen to the other in terms of discomfort especially for muscle strengthening purpose.

As shown in Fig. 4, T_{sk} did not change during exercise but increased significantly in the stimulated leg (~2 C°) and decreased in the control leg (~1 C°) during recovery period for both stimulation conditions. It does not appear that the increases in T_{sk} are associated with the discomfort of EMS. T_{sk} reflects the skin blood flow, and it increases as a result of a vasodilation in skin blood vessels (11, 39). The delayed increase in T_{sk} may suggest that little or no changes in skin blood flow were induced during isometric contractions, but increases in skin blood flow occurred after EMS. The decrease in T_{sk} in the control leg was unexpected. However, Bishop et al. (2) reported that blood flow decreased in the hand skin during a leg exercise, and Cotzias and Marshall (8) also reported a vasoconstrictor response of the cutaneous circulation occurred in the contralateral forearm when isometric handgrip exercise was performed with the other arm. The similar changes in T_{sk} between the alternating and pulsed current EMS reflect a similar muscle usage in the two conditions.

Blood lactate increased similarly in alternating current and pulsed current EMS (Table 2). The magnitude of increase in blood lactate was ~20% less than that reported after EMS (16) in which 40 isometric contractions of the knee extensors were evoked electrically in two legs simultaneously. It is likely the

muscle volume involved in exercise has an effect on the blood lactate response. The hormonal responses to resistance exercise have been well documented (19); however, little information is available on the effects of EMS on hormonal responses. Two studies (16, 34) reported changes in GH after EMS in which pulsed current was used to stimulate the knee extensors of both legs. The present study showed that EMS increased GH by 400% and testosterone by 150% (Table 2). The magnitude of increase in GH in the present study was less than half of that reported in the previous studies (16, 34). This could be due to the difference in the volume of stimulated muscles, i.e., that the knee extensors of both legs were stimulated in the previous studies, but only one leg was stimulated in the present study. The magnitude of increase in testosterone after EMS was similar to that reported following four sets of slow concentric exercise of knee extensors at 50% one repetition maximum (1RM) to failure (10). It is interesting that stimulation of only knee extensors of one leg increased testosterone to a similar level as resistance exercise in which more muscles mass are involved. Jubeau et al. (16) reported that the increase in GH was higher after EMS compared with voluntary contractions of the knee extensors when both were performed at the same torque output and speculated that pain during EMS might be associated with the greater GH release in EMS than voluntary contractions. It might be that EMS is effective for stimulating anabolic hormone release to a greater extent than voluntary contractions.

It was expected to see increases in IGF-1 after EMS because GH stimulates IGF-1 secretion (44). However, no significant changes in IGF-1 were evident up to 45 min post-EMS in the present study. It is important to note that the time course of changes in IGF-1 is different from that of GH or testosterone, such that IGF-1 increases 3–9 h following resistance exercise (14, 17). Thus it is possible that changes in IGF-1 would have been missed. Further investigation is necessary to track the IGF-1 changes following EMS for an extended period. The constant decrease in cortisol is likely due to the circadian rhythm (42), since all EMS sessions in the present study were performed in the morning, and the time between the pre-EMS blood sample and the last blood sample was ~3 h. It is reported that cortisol decreases ~300 nmol/l over the 3-h period from 8 AM to 11 AM (42), whereas the magnitude of the decrease was approximately half (~150 nmol/l) in a similar time frame in the present study. Sartorio et al. (34) reported that cortisol decreased at 1 h after the first EMS bout consisting of 20 isometric contractions started between 8 and 8:30 AM but increased significantly for 30 min following the second EMS bout that was performed 2 h after the first bout. Thus it is possible that EMS increased or at least attenuated the decrease in cortisol in the circadian rhythm, which would suggest catabolic aspects of EMS.

The changes in MVC, muscle soreness, and plasma CK activity after EMS exercise suggest the occurrence of muscle damage following EMS. However, no significant difference between alternating current EMS and pulsed current EMS were evident for any of the parameters (Figs. 5 and 6). Since the baseline MVC was similar, and the torque output during EMS was also similar between the bouts (Fig. 3C), it seems reasonable to assume that mechanical stress to the muscles was similar between the conditions. It is known that the level of force produced during lengthening contractions is a strong predictor of muscle dam-

age (50). Thus it appears that the waveform itself does not affect the magnitude of muscle damage (21), but the similar intensity of muscle contractions between the two EMS conditions was the reason for the nonsignificant differences in the muscle damage characteristics.

As shown in Fig. 5, the decreases in MVC at the angle of stimulation (100°) were significantly greater and longer lasting compared with other angles (40° and 70°). It should be noted that the isometric contractions were performed at 100° in the present study, and the magnitude of MVC decrement appears to be angle specific. The overlap of myosin and actin in isometric contractions at a long length is less compared with that at a short muscle length (5), which may give more mechanical stress over sarcomeres, and cause a disruption to cross bridge (9). Changes in MVC and plasma CK activity have been reported to be greater following eccentric exercise of elbow flexors at long muscle lengths compared with short muscle length (30). Several studies (30, 35) have reported that isometric contractions at a long muscle length induce muscle damage but not at a short muscle length. Nosaka et al. (29) found that muscle damage following intermittent isometric contractions of the elbow flexor induced by EMS was minimal when the biceps brachii was stimulated at a short muscle length (90°). However, our recent study (unpublished) found that when the biceps brachii was stimulated at a long muscle length (160°), EMS-evoked isometric contractions resulted in appreciable changes in muscle damage markers such as MVC, muscle soreness, and plasma CK activity. Thus it seems likely that the cause of muscle damage was not EMS itself but repeated isometric contractions at a long muscle length (1).

Changes in muscle soreness following EMS were similar to those reported in previous studies in which isometric contractions of the knee extensors were evoked by EMS (1, 16). The magnitude of increase in plasma CK activity in the present study was approximately half of that reported in the previous study (16). The amount of stimulated muscles was different between the previous study (two legs) and the present study (one leg), and this could explain the difference. Our previous study (1) showed that the magnitude of muscle damage was significantly attenuated in the second EMS bouts performed 2 wk after the initial bout using pulsed current. It seems likely that this is also the case for alternating current EMS; however, this should be investigated in future studies.

In conclusion, alternating and pulsed current have a similar effect on force production, RPE, skin temperature, hormonal responses, and muscle damage, when the stimulation parameters except the waveform were matched between the two. These findings suggest that acute effects are similar between alternating and pulsed current EMS; thus the waveform itself is less important for EMS, if an EMS machine has an capacity to maximally stimulate a muscle when other parameters such as stimulation intensity, frequency, and pulse duration are the same. Considering the fact that a pulsed current stimulator is less expensive and more portable than an electrical stimulator that can deliver alternating current, pulsed current EMS may be more advantageous over alternating current EMS, especially when it is used for muscle training. It is important to note that the present study focused on the use of EMS in muscle training of healthy men; therefore it is necessary to examine women, elderly individuals, and clinical populations in future studies. Chronic effects of the use of different current in a treatment or

a training program cannot be speculated from the present study. Thus further study is warranted to compare the effects of chronic use of EMS on muscle adaptation between alternating current and pulsed current EMS for healthy and clinical populations.

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DISCLOSURES

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