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Effects of Two Modalities of Whole-body Electrostimulation Programs and Resistance Circuit Training on Strength and Power

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ABSTRACT

The main purpose of this study was to compare the effects on strength and muscle power of a training program based on two different modalities of whole-body electrostimulation (WB-EMS) with respect to a resistance-training program aimed at improving dynamic strength. Twenty-two subjects participated in this study: Thirteen male (age 25.2 ± 2.8 years; height 1.78 ± 0.1 m; body mass 72.8 ± 6.4 kg; body fat 11.6 ± 2.3 %) and nine female (age 28.2 ± 3.5 years; height 1.63 ± 0.05 m; body mass 56.8 ± 7.6 kg; body fat 19.1 ± 4.7 %). Participants were randomly assigned to three groups that underwent three different 6-week training programs: two modalities of WB-EMS, based on different electrical parameters (experimental), and circuit training with overloads (control). Force-velocity curves were calculated for each participant before and after treatment. All groups improved their level of strength and muscle power (paired sample t-Test, $p < 0.01$; $d > 1$) with a similar magnitude. No significant differences were observed between groups (two-way 2 × 3 Anova, $p > 0.05$) at the end of the experimentation. This study suggests that WB-EMS might be considered as a valid and faster alternative – or an important complementary procedure – to a traditional overload-based resistance-training program for the development of the DS.

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Introduction

Background

Electrical muscle stimulation (EMS) consists of local application of an electric current to elicit a muscle contraction [1]; in sports training, the most commonly used technique is percutaneous electrical stimulation, where the electrostimulation is applied to the muscular belly [2]. Several studies performed both in the medical and sports fields have extensively analyzed the principles and the parameters of the EMS [mainly considering the intensity of the electrical stimulus (Amp), the frequency (Hz), and the width of the impulse] and the physiological adaptations to the EMS training [3–12, 27]. Certainly, fewer studies have taken into account whole-body electromyostimulation (WB-EMS), a training method associated with a voluntary pre-contraction both isometric or dynamic [10, 13]. The WB-EMS is a technique that can stimulate various muscle

groups simultaneously by the means of special suits fitted with multiple electrodes. As reported in the literature, with this technique it is clearly possible to obtain improvements in strength and muscular power, body composition [14], physical performance such as jumping ability and sprinting [15, 16], and in the specific technical skills of some sports disciplines [17]. However, it remains unclear whether electrical stimulation and voluntary muscle contraction can be considered as complementary stimuli of different nature from the physiological point of view, due to the different recruitment patterns: In electrostimulation, larger motor units might be recruited before the smaller motor units, exactly the opposite of what happens in a voluntary contraction, according to Henneman's Size Principle. It is now also demonstrated that the effects of training with the WB-EMS method consist of positive adaptations that directly affect the performance of healthy subjects or athletes [14, 17].

Recently, the study by Micke et al. [7] has shown that a WB-EMS program provides similar improvements, compared to a traditional training program, in terms of maximal isometric strength (F_{max}) and maximal isoinertial power (P_{max}) for the leg muscles, measured through the leg extension (LE), leg curl (LC), and leg press (LP) machines, of jumping performances, measured by the means of squat jump (SJ), counter movement jump (CMJ), drop jump (DJ) and standing long jump (SLJ), of sprinting abilities measured through linear (30 m) and shuttle sprinting (3 x10 m).

Aims

The purpose of this study was to assess the effects of a 6-week training program on strength and muscle power of upper and lower limbs, using a WB-EMS training ▶ **Fig. 1** with two different intensity protocols [9], compared to a traditional resistance-training program with overloads. Strength and muscle power were measured and assessed in the 3 groups before and after treatment in comparable conditions, through the estimation of the relevant force-velocity curves, so to obtain information on the different possible adaptations of the force expressions, ranging from maximal strength to explosive power.

The novelty of our study was represented by the assessing procedures that gave us a broader insight from what was currently available in the scientific literature about the mechanics of muscle contraction.

Materials and Methods

Experimental approach to the problem

Participants were randomly assigned to 3 different groups: one control group (CT-DS, n = 8) and two experimental ones (WB-EMS1, n = 6; WB-EMS2, n = 8).

Three distinct phases were arranged:

1. Initial testing, carried out in the week prior to the experimental phase and aimed at measuring the baseline levels of some physical parameters (anthropometric data, values of strength and power of the upper and lower limbs in order to define the relevant force-velocity curves); after that, the participants were randomly assigned to the different training (treatment) groups.
2. Administration of different treatments, consisting of:
   a. Circuit Training – Dynamic Strength (CT-DS)
   b. Whole Body Electro-stimulation – protocol 1 (WB-EMS1)
   c. Whole Body Electro-stimulation – protocol 2 (WB-EMS2)

In this study we decided to verify the effect of two different stimulus frequencies (i. e. 50 vs. 85 Hz – see ▶ **Table 1**) induced by two different WB-EMS protocols, as already proposed in other researches [8]. According to Paillard et al. [8] WB-EMS protocol 1, based on a frequency of 50 Hz, is to be included in the most efficient methods for the development of muscle strength. WB-EMS protocol 2, based on a frequency of 85 Hz, could instead have strong inhibitory effects on muscle contraction and induce afferent signals including a possible nociceptive component.

3. Final testing, designed to measure the changes in the neuromuscular status (dependent variables) induced by the different types of treatment (independent variables) and carried out in the week after the experimental phase.

Subjects

Twenty-two subjects participated in this study: thirteen male (n = 13; age 25.2 ± 2.8 years; height 1.78 ± 0.1 m; body mass 72.8 ± 6.4 kg; body fat 11.6 ± 2.3 %) and nine female (n = 9; age 28.2 ± 3.5 years; height 1.63 ± 0.05 m; body mass 56.8 ± 7.6 kg; body fat 19.1 ± 4.7 %).

The sample consisted of students of Physical Education (n = 22) – Faculty of Medicine and Surgery – University of Rome "Tor Vergata," who usually performed at least three training sessions per week, mostly soccer, thus holding a medium-high fitness status.

Written informed consent was obtained from all the participants after familiarization and explanation of the benefits and risks involved in the procedures of this study. All participants were informed that they were free to withdraw from the study at any time without penalty. The Institutional Research Board (Ethical Committee of the School of Sports and Exercise Sciences, University of Rome "Tor Vergata", Faculty of Medicine and Surgery) approved our research protocol and provided clearance for the procedures before the commencement of this study. All procedures were carried out in accordance with the Declaration of Helsinki (1975, revised in 2013) of the World Medical Association as regards the conduct of clinical research. We confirm that we have read and understood the IJSM's ethical standards document [18] and that this study meets the ethical standards of the journal.

Before undergoing test procedures, all participants were required to provide a certificate of medical fitness, excluding pathologies and contraindications to high-intensity physical activities and treatments based on electrostimulations.

Procedures

All the experimentation took place at the Human Performance and Training Laboratory "Carmelo Bosco" – University of Rome "Tor Vergata".

In the week prior to the experimentation, assessment testing with increasing overloads to determine the initial force-velocity curve for all the participants was administered. To do so, the barbell bench press and squats on the Smith machine were used. The value of 1-RM has been calculated for each participant applying the formula suggested by Brzycki [19].

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To draw the velocity-force curve, we considered the four loads described in ▶ **Table 2**, obtained as percentages of the previously calculated 1-RM, both for the upper limbs loads (barbell bench press) and for the lower limbs (squatting at the Smith Machine), for both males and females.

After that, the participants were randomly split into the three groups. Then the research protocol started, including 12 training sessions carried out over 6 weeks.

The first group (CT-DS) performed circuit training in the gym aimed at improving dynamic strength (DS), using overloads.

Circuit training comprised the following exercises: barbell bench press, dumbbell biceps curl, lat pulldown, prone plank (with no overload), squatting (using the Smith machine), prone leg curl, standing calf.

Ten repetitions were performed for three sets consecutively for each exercise with a load equal to 65 % of one repetition maximum (1-RM). Resting time among series was 1 min and 30 s. A fitness coach personally followed the participants of the CT-DS group, supervising the whole training session.

The second (WB-EMS1) and the third group (WB-EMS2) performed the whole-body electro muscle stimulation (WB-EMS) training according to the electrical and methodological parameters described in ▶ **Table 1**.

During the WB-EMS treatments, each participant was asked to perform, exactly at the start of the impulse, the following set of ten isometric exercises (2 min per exercise), without any machine or external loads: abdominal cross crunches, ¼ squat and abdominal crunch, ½ squat and pectoral exercise, ½ squat and arms extension, ½ squat and reverse butterfly, ½ squat and lat exercise, ½ squat and biceps curl, ½ squat and triceps push down, ½ squat, forward lunges.

In order to obtain the force-velocity curves (▶ **Figs. 2–5**) after the training period, a new testing phase was implemented in the week following the end of experimentation, in order to evaluate the physical effects of the different treatments on the muscle strength and power. To assess the possible increases, considered at the various loading levels (%), participants were tested with the same loads used in the initial tests, thus maintaining the same loads to be accelerated.

Instrumentation

To determine the force-velocity curves, a Gyco accelerometer (Microgate, Bolzano, Italy, 2015) with a 1000 Hz sampling frequency was used. As for the training with WB-EMS (XBody, Actiwave, Győr, Hungary), subjects wore a special gym suit fitted with multiple electrodes, (provided by Urban Fitness, Milan, Italy – ▶ **Fig. 1**), which simultaneously stimulated the following muscle groups: brachial biceps, brachial tricepses, trapezius, dorsal muscles, pectorals, abductors, gluteus maximus, femoral quadriceps and femoral biceps. The gym suit was carefully wetted to allow the best electrical behavior of the device and consequently the best performance during the training session lasting 20 min. The CT-DS training group performed physical exercises that solicited the same muscular districts through the use of conventional gym equipment such as dumbbells, barbells and iso-inertial machines.

On experimentation days, the lab setting was arranged in two dedicated areas to carry out the circuit training with the overloads and the session of WB-EMS training: The two activities were performed at the same time and with a continuous assistance from the researchers involved in this study.

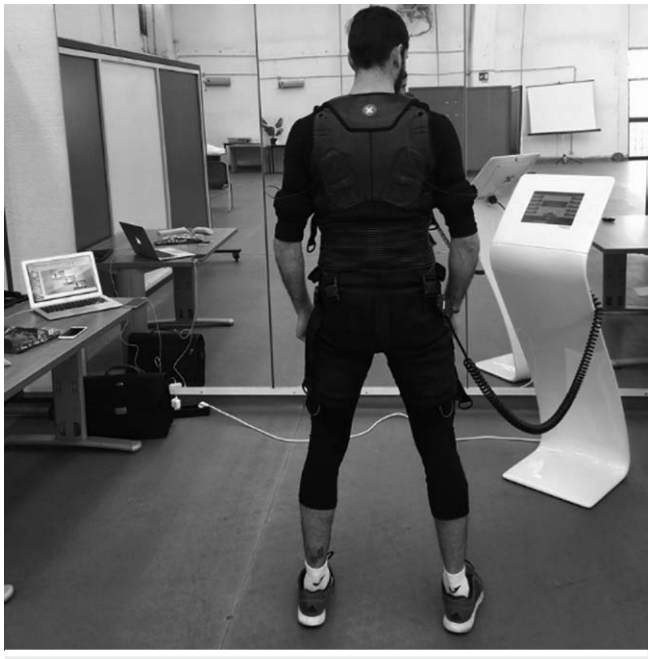
▶ **Table 1** Electrical and methodological parameters of the whole body electrostimulation protocols adopted in this study.

Parameters	WB-EMS1	WB-EMS2
Training Session Duration	20 min	20 min
Pulse duration	4 s	4 s
Pause between pulses	6 s	4 s
Duty cycle (per minute)	24”/36” (pulse to rest)	32”/28” (pulse to rest)
Pulse frequency	50 Hz	85 Hz
Pulse width	350 ms	350 ms
Pulse ramp	0.5 s	0.1 s
Perceived pulse intensity	Borg Scale CR-20 ranging from 14 to 16 (“somewhat hard” to “hard”)	Borg Scale CR-20 ranging from 14 to 16 (“somewhat hard” to “hard”)

▶ **Table 2** Force-velocity curve, initial loading parameters.

	Loading Parameters (as % 1-RM)
Load 1 (L1)	15
Load 2 (L2)	35
Load 3 (L3)	65
Load 4 (L4)	85

1-RM = one repetition maximum estimated through Brzycki’s formula (1993).



▶ **Fig. 1** The gym suit with multiple electrodes used in this study.

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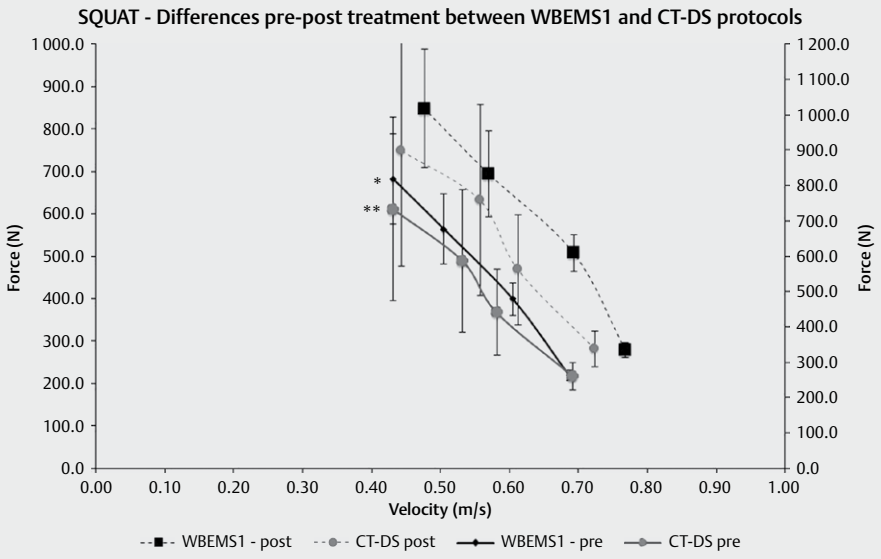
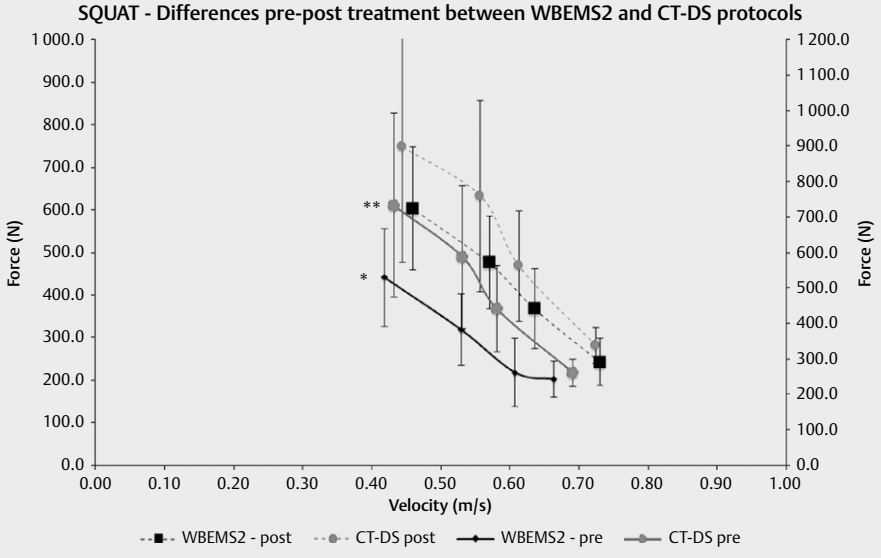


▶ **Fig. 2** Squatting test. Force-velocity curves drawn before and after treatment (mean values ± SD; Y axis SD = Force): WB-EMS1 protocol vs. CT-DS protocol (control) – Note the increased values posttreatment ($p < 0.05$, Cohen's $d > 1$).



▶ **Fig. 3** Squatting test. Force-velocity curves drawn before and after treatment (mean values ± SD; Y axis SD = Force): WB-EM2 protocol vs. CT-DS protocol (control) – Note the increased values posttreatment ($p < 0.05$, Cohen's $d > 1$).

Statistical analyses

Data are presented as mean ± SD and confidence intervals (95 % CIs) for the means of the differences of the pre-post testing.

The assumption of normality was assessed using the Shapiro-Wilk test.

The Intraclass Correlation Coefficients (ICC) for average measure are provided as indices of relative reliability of the tests.

To test the differences before and after the treatments (within-effects) the t-Test for paired samples was performed. Effect Size (ES) indicators as Cohen's d were provided and they were computed according to the formula $d = t/\sqrt{n}$ [26], where t = paired sample t-Test value and n = number of observations. Absolute ES of 0.20, 0.50, 0.80, > 1 represent small, medium, large and huge effects, respectively.

To point out the possible differences among groups (between) – pre and post the administration of the treatments – a two-way analysis of variance [2 (pre and post treatment) × 3 (control and the two experimental conditions)] was used to determine possible main effects or interactions and, if so, to compare the significant differences among the three groups. Effect Size (ES) in ANOVA was

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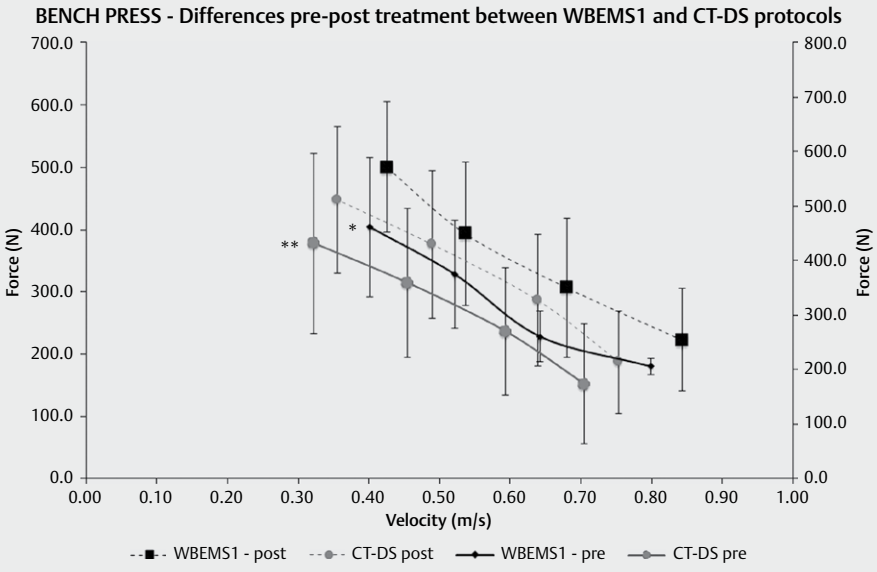
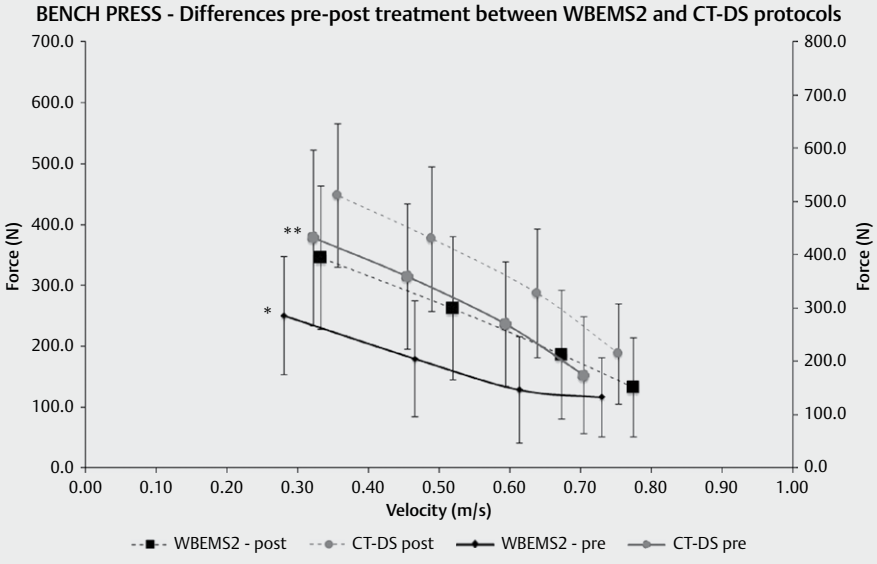


▶ **Fig. 4** Bench press test. Force-velocity curves drawn before and after treatment (mean values ± SD; Y axis SD = Force): WB-EMS1 protocol vs. CT-DS protocol (control) – Note the increased values post-treatment ($p < 0.05$, Cohen's $d > 1$).



▶ **Fig. 5** Bench press test. Force-velocity curves drawn before and after treatment (mean values ± SD; Y axis SD = Force): WB-EM2 protocol vs. CT-DS protocol (control) – Note the increased values post-treatment ($p < 0.05$, Cohen's $d > 1$).

computed as partial η^2, to assess meaningfulness of differences, with $\eta^2 < 0.01$, $0.01 < \eta^2 < 0.06$, $0.06 < \eta^2 < 0.14$ and $\eta^2 > 0.14$, as trivial, small, moderate and large ES, respectively.

A post hoc power analysis was used to verify whether a sample size of 22 subjects, assigned in three groups, was sufficient to detect the effect of the interventions on the force and power results, based on the observed pre- and post-treatment mean values and SDs. It suggested that the data could be interpreted with a large to very large effect size (ES) level, ranging from 2.71 ± 1.07, 2.96 ± 1.19, 2.49 ± 0.73 and 1.94 ± 0.37 (mean ± standard deviation) and power levels > 0.95 when significance was set at an alpha level of 0.05, for squatting tests, force and power values and bench press tests, force and power values, respectively.

The corresponding P values are provided for each analysis. The value of statistical significance was accepted with $P \leq 0.05$. SPSS 20.0 for Windows was used to analyze and process the collected data.

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Results

As a measure of the relative reliability of measurements obtained during the testing procedures, the intraclass correlation coefficients were computed for all the observations collected, before and after the different treatments (▶ **Tables 3** and **4**).

Squatting testing carried out before and after treatments: Force and Power

Force-velocity curves, drawn before and after the treatments are provided in ▶ **Figs. 2–3**.

The descriptive statistics [mean ± standard deviation, incremental percentages of the differences (Δ), confidence interval for the differences (95 %)] and the relevant values (t; degrees of freedom, p-values and Cohen's d as effect size estimators) of the paired sample t-tests performed to investigate the within effects of the treatments, both for the force values (N) and the power ones (W) are provided in ▶ **Tables 5** and **6**. These results highlighted the large within-effects obtained by all the different treatments considered on the participants ($p < 0.01$; $d > 1$) and achieved during the time of experimentation. These finding are also evidenced by the 2 x 3 two-way ANOVA (within effect) that we performed with very large effect sizes (▶ **Tables 7** and **8**).

The between-group differences (before and after the treatments), both for the force values (N) and power values (W) were verified through the two-way analysis of variance (ANOVA). The relevant results are provided in ▶ **Tables 7** and **8**. The effect sizes, estimated as partial eta squared values, are considered. According to these statistical analyses, no evident differences ($p > 0.05$) were found between the different treatments, highlighting the substantial parity of the effects induced by the training modes adopted in this study. We observed some interactions too, suggesting possible slight differences between the groups but a post hoc analysis with Bonferroni correction did not reveal any significant differences ($p > 0.05$).

▶ **Table 3** Intraclass correlation coefficients in squatting tests (Force and Power).

Squatting Test (Force)	ICC (average measures)	CI (95 %)	p
L1 (pre-post)	0.943	−0.037–0.989	<0.001
L2 (pre-post)	0.985	0.255–0.997	<0.001
L3 (pre-post)	0.980	0.369–0.996	<0.001
L4 (pre-post)	0.989	0.698–0.997	<0.001
Squatting Test (Power)			
L1 (pre-post)	0.912	−0.048–0.983	<0.001
L2 (pre-post)	0.958	0.152–0.991	<0.001
L3 (pre-post)	0.954	−0.023–0.991	<0.001
L4 (pre-post)	0.971	0.131–0.994	<0.001

ICC = Intraclass correlation coefficient; **CI** = confidence interval. **L1** = loading 15 % 1-RM; **L2** = loading 35 % 1-RM; **L3** = loading 65 % 1-RM; **L4** = loading 85 % 1-RM; (pre-post) = pre treatment – post treatment).

▶ **Table 4** Intraclass correlation coefficients in barbell bench press tests (Force and Power).

Barbell bench press Test (Force)	ICC (average measures)	CI (95 %)	p
L1 (pre-post)	0.992	0.626–0.998	<0.001
L2 (pre-post)	0.983	0.472–0.996	<0.001
L3 (pre-post)	0.993	0.522–0.999	<0.001
L4 (pre-post)	0.988	0.358–0.998	<0.001
Barbell bench press Test (Power)			
L1 (pre-post)	0.980	0.344–0.996	<0.001
L2 (pre-post)	0.963	0.072–0.992	<0.001
L3 (pre-post)	0.983	0.316–0.996	<0.001
L4 (pre-post)	0.976	0.288–0.995	<0.001

ICC = Intraclass correlation coefficient; **CI** = confidence interval. **L1** = loading 15 % 1-RM; **L2** = loading 35 % 1-RM; **L3** = loading 65 % 1-RM; **L4** = loading 85 % 1-RM; (pre-post) = pre treatment – post treatment).

Barbell bench press testing carried out before and after treatments: Force and Power

Force-velocity curves, drawn before and after the treatments are provided in ▶ **Figs. 4** and **5**.

The descriptive statistics [mean ± standard deviation, incremental percentages of the differences (Δ), confidence interval for the differences (95 %)] and the relevant values (t; degrees of freedom, p-values and Cohen's d as effect size estimators) of the paired sample t-tests performed to investigate the within effects of the treatments, both for the force values (N) and the power ones (W) are provided in ▶ **Tables 9** and **10**. These results highlighted the large within effects obtained by all the different considered treatments on the participants ($p < 0.01$; $d > 1$), achieved during the time of the experimentation. These finding is also evidenced by the 2 x 3 two-way ANOVA (within effect) we performed with very large effect sizes (▶ **Tables 11** and **12**).

The between-group differences (before and after the treatments), both for the force values (N) and power values (W) were verified through the two-way analysis of variance (ANOVA). The relevant results are provided in ▶ **Tables 11** and **12**. The effect sizes, estimated as partial eta squared values, are considered. According to these statistical analyses no evident differences ($p > 0.05$) were found between the different treatments, highlighting the substantial parity of the effects induced by the training modes adopted in this study. We observed some interactions too, suggesting of possible slight differences between the groups but a post hoc analysis with Bonferroni correction did not confirm any significant differences ($p > 0.05$).

Discussion

This is the first study, to our knowledge, to assess the effects of WB-EMS on the whole-muscle capacity using force-velocity curves [25]; the study thus investigates the complex of neuromuscular adaptations induced by this treatment.

The results of the current study showed that 6 weeks of WB-EMS protocol compared to a traditional resistance training with overloads did not lead to significant differences in outcomes. The three training programs, in other words, provide similar results in terms of efficacy of response at the end of the experimental session.

These results are in agreement with those reported by Kemmler et al. [14] and Micke et al. [7], confirming the possible alternative

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▶ **Table 5** Squatting. Force-velocity curve loading parameters: Force values recorded pre and post the different experimental and control treatments (WB-EMS 1, WB-EMS 2 and CT-DS) in the different groups. Within-group differences (paired sample t Test). Force values are expressed in Newton (N).

Loading	WB-EMS 1					WB-EMS 2					CT-MDS				
	Pre Tr (N)	Post Tr (N)	Δ (%)	CI 95%	PS t-Test	Pre Tr (N)	Post Tr (N)	Δ (%)	CI 95%	PS t-Test	Pre Tr (N)	Post Tr (N)	Δ (%)	CI 95%	PS t-Test
L1	262.48 (14.97)	279.22 (16.66)	+6.00	LB = −22.38 UB = −11.10	t = −7.63 df = 5 P = **0.001** d = −3.12	243.11 (51.00)	261.59 (54.66)	+7.07	LB = −23.08 UB = −13.89	t = −9.51 df = 7 P < **0.001** d = −3.36	261.40 (38.00)	282.20 (41.80)	+7.37	LB = −26.02 UB = −15.58	t = −9.42 df = 7 P < **0.001** d = −3.33
L2	478.80 (46.98)	507.91 (43.50)	+5.73	LB = −22.38 UB = −11.10	t = −8.28 df = 5 P < **0.001** d = −3.38	367.17 (95.94)	383.26 (94.01)	+4.20	LB = −22.36 UB = −9.82	t = −6.07 df = 7 P = **0.001** d = −2.14	440.64 (121.20)	468.79 (130.17)	+6.00	LB = −38.76 UB = −17.54	t = −6.27 df = 7 P < **0.001** d = −2.21
L3	676.77 (98.79)	694.49 (101.64)	+2.55	LB = −22.38 UB = −11.10	t = −4.23 df = 5 P = **0.008** d = −1.73	476.22 (100.67)	529.05 (109.33)	+9.98	LB = −62.74 UB = −42.91	t = −12.60 df = 7 P < **0.001** d = −4.45	587.35 (202.37)	633.01 (225.16)	+7.21	LB = −70.07 UB = −21.23	t = −4.42 df = 7 P = **0.003** d = −1.56
L4	818,11 (128,0)	848,04 (139,45)	+3.53	LB = −22.38 UB = −11.10	t = −5.94 df = 5 P = **0.002** d = −2.43	603.77 (138,27)	661.72 (143.56)	+8.76	LB = −70.24 UB = −45.65	t = −11.15 df = 7 P < **0.001** d = −3.94	732.88 (260.20)	749.60 (272.87)	+4.64	LB = −33.82 UB = 0.40	t = −5.94 df = 7 P = **0.054** d = −0.81

L1 = loading 15% 1-RM; L2 = loading 35% 1-RM; L3 = loading 65% 1-RM; L4 = loading 85% 1-RM. Pre Tr = Pre Treatment; Post Tr = Post Treatment; M (SD); N = Newton. Δ (%) = Percentage of variations between pre and post scores (means) CI95% = Confidence Interval for the differences; LB = lower bound; UB = upper bound. PS t-Test = Paired Samples t-Test; t = t values; df = degree of freedom; P = P values (P values in bold are significant); d = Cohen's d values. (Effect Size; ES). Absolute ES of 0.20, 0.50, 0.80, > 1 represent small, medium, large and huge effects, respectively.

▶ **Table 6** Squatting. Force-velocity curve loading parameters: Power values recorded pre and post the different experimental and control treatments (WB-EMS 1, WB-EMS 2 and CT-MDS) in the different groups. Within-group differences (paired sample t Test). Pre and post treatment Power values are expressed in Watt (W).

Loading	WB-EMS 1					WB-EMS 2					CT-MDS				
	Pre Tr (W)	Post Tr (W)	Δ (%)	CI 95%	PS t-Test	Pre Tr (W)	Post Tr (W)	Δ (%)	CI 95%	PS t-Test	Pre Tr (W)	Post Tr (W)	Δ (%)	CI 95%	PS t-Test
L1	180.59 (30.20)	214.97 (34.75)	+15.99	LB = −40.75 UB = −28.01	t = −13.87 df = 5 P < **0.001** d = −5.66	161.17 (40.48)	190.92 (49.29)	+15.58	LB = −38.30 UB = −21.21	t = −8.23 df = 7 P < **0.001** d = −2.91	185.55 (68.29)	216.94 (75.91)	+14.47	LB = −39.53 UB = −23.25	t = −9.12 df = 7 P < **0.001** d = −3.22
L2	292.57 (61.85)	355.55 (76.62)	+17.71	LB = −84.33 UB = −41.61	t = −7.58 df = 5 P = **0.001** d = −3.09	228.16 (91.44)	248.90 (33.76)	+8.33	LB = −20.74 UB = −8.75	t = −6.71 df = 7 P < **0.001** d = −2.37	273.92 (133.84)	313.65 (149.45)	+12.67	LB = −56.68 UB = −22.77	t = −6.27 df = 7 P = **0.001** d = −1.95
L3	349.19 (104.2)	403.23 (113.37)	+13.40	LB = −67.02 UB = −41.06	t = −4.23 df = 5 P < **0.001** d = −4.37	256.95 (95.56)	307.04 (110.72)	+16.31	LB = −63.74 UB = −36.46	t = −8,68 df = 7 P < **0.001** d = −3.07	313.27 (157.18)	372.15 (190.02)	+15.82	LB = −87.41 UB = −30.34	t = −4.88 df = 7 P = **0.002** d = −1.72
L4	362.69 (120.4)	415.64 (139.01)	+12.74	LB = −73.48 UB = −32.41	t = −6.63 df = 5 P = **0.001** d = −2.70	259.36 (111.98)	311.27 (124.63)	+16.68	LB = −65.36 UB = −38.45	t = −9.124 df = 7 P < **0.001** d = −3.22	326.61 (166.02)	357.42 (187.35)	+8.62	LB = − −52.25 UB = −9.37	t = −3.40 df = 7 P = **0.01** d = −1.20

L1 = loading 15% 1-RM; L2 = loading 35% 1-RM; L3 = loading 65% 1-RM; L4 = loading 85% 1-RM - Pre Tr = Pre Treatment; Post Tr = Post Treatment; M (SD); W = Watt. Δ (%) = Percentage of variations between pre and post scores (means) - CI95% = Confidence Interval for the differences; LB = lower bound; UB = upper bound; PS t-Test = Paired Samples t-Test; t = t values; df = degree of freedom; P = P values (P values in bold are significant); d = Cohen's d values. (Effect Size; ES). Absolute ES of 0.20, 0.50, 0.80, > 1 represent small, medium, large and huge effects, respectively.

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▶ **Table 7** Two way ANOVA [2 (pre-post) x 3 (control and experimental conditions)] - Squatting. Force-velocity loading parameters: within, between-group differences and interactions found in the force values (WB-EMS1 vs. WB-EMS2 vs. CT-DS) recorded pre and post the different experimental and control treatments.

	Within			Between			Interaction		
	F_{df}	P	$\eta^2_{part.}$	F_{df}	P	$\eta^2_{part.}$	F_{df}	P	$\eta^2_{part.}$
L1	$227.620_{1,19}$	**<0.001**	0.923	$0.552_{2,19}$	0.585	0.055	$0.878_{2,19}$	0.432	0.085
L2	$129.698_{1,19}$	**<0.001**	0.872	$2.695_{2,19}$	0.093	0.221	$3.992_{2,19}$	**0.036**	0.296
L3	$82.264_{1,19}$	**<0.001**	0.812	$2.535_{2,19}$	0.106	0.211	$5.767_{2,19}$	**0.011**	0.378
L4	$95.810_{1,19}$	**<0.001**	0.835	$1.837_{2,19}$	0.186	0.162	$12.844_{2,19}$	**<0.001**	0.575

L1 = loading 15 % 1-RM; L2 = loading 35 % 1-RM; L3 = loading 65 % 1-RM; L4 = loading 85 % 1-RM. Two way ANOVA [2 x 3]: F = F values and degrees of freedom; P = P values (P values in bold are significant); η^2_{part} = Partial ETA squared as Effect Size; (ES). Absolute partial ETA squared values < 0.01; 0.01 < η^2_{part} < 0.06; 0.06; < η^2_{part} < 0.14; > 0.14 represent trivial, small, moderate and large effects, respectively.

▶ **Table 8** Two way ANOVA [2 (pre-post) x 3 (control and experimental conditions)] - Squatting. Force-velocity loading parameters: within, between-group differences and interactions found in the Power values (WB-EMS1 vs. WB-EMS2 vs. CT-MDS) recorded pre and post the different experimental and control treatments.

	Within			Between			Interaction		
	F_{df}	P	$\eta^2_{part.}$	F_{df}	P	$\eta^2_{part.}$	F_{df}	P	$\eta^2_{part.}$
L1	$263.541_{1,19}$	**<0.001**	0.933	$0.496_{2,19}$	0.617	0.050	$0.446_{2,19}$	0.647	0.045
L2	$126.684_{1,19}$	**<0.001**	0.870	$1.134_{2,19}$	0.343	0.107	$10.598_{2,19}$	**0.001**	0.527
L3	$112.377_{1,19}$	**<0.001**	0.855	$0.898_{2,19}$	0.424	0.086	$0.764_{2,19}$	**0.028**	0.545
L4	$100.737_{1,19}$	**<0.001**	0.841	$0.896_{2,19}$	0.425	0.086	$2.697_{2,19}$	0.093	0.221

L1 = loading 15 % 1-RM; L2 = loading 35 % 1-RM; L3 = loading 65 % 1-RM; L4 = loading 85 % 1-RM. Two way ANOVA [2 x 3]: F = F values and degrees of freedom; P = P values (P values in bold are significant); η^2_{part} = Partial ETA squared as Effect Size; (ES). Absolute partial ETA squared values < 0.01; 0.01 < η^2_{part} < 0.06; 0.06; < η^2_{part} < 0.14; > 0.14 represent trivial, small, moderate and large effects, respectively.

or contributive use of the WB-EMS methods to the efficient training of strength and power. In particular, with respect to the study by Micke et al. (2018), which focused on the strength and power parameters of the leg muscles, our study added new findings investigating the effects of WB-EMS programs on strength and power parameters of upper and lower limbs using force-velocity curves as suggested by Bosco and Komi [20], Bosco [21], and Zatsiorsky and Kraemer [22]. In particular, ▶ **Figs 2–5** indicate the right shift of the entire curves, after the three treatments, demonstrating that both the area of force and that of velocity have increased in a similar way, thus causing harmonics adaptations in all the expressions of muscular force we considered [23]. The wide and harmonic variations of the neuromuscular status observed in all the points of the curves, confirmed by the large effect size values found (d > 1), show the adaptations of both fast and slow fibers to the electric stimulus, despite a period of training of only 6 weeks and training sessions lasting only 20 min. As can be seen in ▶ **Tables 5, 6 ,9** and **10**, the post-treatment increase is very evident both in the squat and bench press tests, as confirmed by the high percentage increase values reported, for both the expressions of force (range of increase: 2.55–14.99 %) and power (7.29–22.13 %). All data processing shown in the pre-post treatment comparisons show very high statistical significance (p < 0.001) and large effect size.

Observing the different behavior of the post-treatment variations in the values of force and power, the latter varies more widely. This allows us to hypothesize a higher involvement of the fast fibers compared to the slow ones [24]. The fact that the improvements observed after the three treatments are similar is evidenced by the analysis of the variance performed, which shows rather high p values (p > 0.05). Indeed, there are no significant differences between treatments except for some effect size values (η^2_{part} > 0.14, see ▶ **Tables 7**, **8**, **11** and **12**). This allows us to state that the treatments, although similar in the recorded effects, are not perfectly superimposable. Considering the data reported in the graphs and in the Tables, a trend is observed for the WB-EMS treatments that appear a bit more effective, as indicated by the effect size (Cohen's d), of the first protocol (WB-EMS1) compared to the other two.

All the treatments considered were effective, showing an increase (p < 0.01; d > 1) of strength and muscle power, which were the physical parameters chosen as indicators of muscle performance. The force-velocity curves calculated before and after treatment, indicated a harmonic growth of the force-velocity curves' loading parameters, for each training session considered. Thus our attention might focus on the managing aspect of these means of training, underlining the evident time-saving made possible by WB-EMS, whose training sessions usually last 20 min, compared to the traditional ones, lasting in average more than an hour.

The training sessions we designed were quite demanding, especially for the WB-EMS1 and the CT-DS. With regard to WB-EMS2, we adopted the manufacture's guidelines, particularly designed for a broader population of possible users.

The efficacy of the different training sessions suggests that these approaches can be used in different populations with a high level of fitness or in non-athletic customers, as the WB-EMS2 protocol was judged by the participants to be a method without "annoying sensations." In addition, WB-EMS training is useful for people who want to keep a high level of muscle fitness in a short time. In fact, in this study the participants have spent only 4 h in electrostimula-

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▶ **Table 9** Barbell bench press. Force-velocity curve loading parameters: Force values recorded pre and post the different experimental and control treatments (WB-EMS 1, WB-EMS 2 and CT-DS) in the different groups. Within-group differences (paired sample t Test). Force values are expressed in Newton (N).

Loading	WB-EMS 1					WB-EMS 2					CT-MDS				
	Pre Tr (N)	Post Tr (N)	Δ (%)	CI 95%	PS t-Test	Pre Tr (N)	Post Tr (N)	Δ (%)	CI 95%	PS t-Test	Pre Tr (N)	Post Tr (N)	Δ (%)	CI 95%	PS t-Test
L1	206.01 (75.40)	222.97 (82.07)	+7.57	LB = −25.66 UB = −8.09	t = −4.93 df = 5 P = **0.004** d = −2.01	132.54 (74.28)	146.31 (81.97)	+9.41	LB = −20.34 UB = −7.18	t = −4.94 df = 7 P < **0.002** d = −1.74	173.75 (109.47)	187.30 (117.94)	+7,23	LB = −21.42 UB = −5.67	t = −4.06 df = 7 P < **0.005** d = −1.43
L2	260.98 (99.45)	306.99 (111.89)	+14.99	LB = −60.79 UB = −31.22	t = −7.99 df = 5 P < **0.001** d = −3.26	185.98 (100.46)	204.77 (105.24)	+9.17	LB = −23.80 UB = −13.76	t = −8.85 df = 7 P < **0.001** d = −3.13	270.35 (116.65)	286.51 (120.25)	+5.64	LB = −21.44 UB = −10.88	t = −7.24 df = 7 P < **0.001** d = −2.56
L3	375.13 (114.65)	393.35 (114.99)	+4.63	LB = −29.69 UB = −6.75	t = −4.08 df = 5 P = **0.010** d = −1.66	262.10 (109.72)	285.66 (118.14)	+8.25	LB = −31.96 UB = −15.19	t = −6.65 df = 7 P < **0.001** d = −2.87	359.59 (136.88)	375.97 (142.76)	+4.36	LB = −22.64 UB = −10.12	t = −6.18 df = 7 P < **0.001** d = −2.19
L4	461.61 (97.89)	500.47 (104.72)	+7.76	LB = −51.04 UB = −26.67	t = −8.19 df = 5 P < **0.001** d = −3.34	345.43 (111.19)	375.35 (117.91)	+7.97	LB = −36.90 UB = −22.96	t = −10.15 df = 7 P < **0.001** d = −3.59	432.27 (165.58)	447.31 (171.36)	+3.36	LB = −20.89 UB = −9.18	t = −6.07 df = 7 P = **0.001** d = −2.14

L1 = loading 15% 1-RM; **L2** = loading 35% 1-RM; **L3** = loading 65% 1-RM; **L4** = loading 85% 1-RM. **Pre Tr** = Pre Treatment; **Post Tr** = Post Treatment; M (SD); N = Newton. **Δ (%)** = Percentage of variations between pre and post scores (means). **CI95%** = Confidence Interval for the differences; LB = lower bound; UB = upper bound; **PS t-Test** = Paired Samples t-Test; **t** = t values; **df** = degree of freedom; **P** = P values (P values in bold are significant); **d** = Cohen's d values. (Effect Size; ES). Absolute ES of 0.20, 0.50, 0.80, > 1 represent small, medium, large and huge effects, respectively.

▶ **Table 10** Barbell bench press. Force-velocity curve loading parameters: Power values recorded pre and post the different experimental and control treatments (WB-EMS 1, WB-EMS 2 and CT-DS) in the different groups. Within-group differences (paired sample t Test). Pre and post treatment Power values are expressed in Watt (W).

Loading	WB-EMS 1					WB-EMS 2					CT-MDS				
	Pre Tr (W)	Post Tr (W)	Δ (%)	CI 95%	PS t-Test	Pre Tr (W)	Post Tr (W)	Δ (%)	CI 95%	PS t-Test	Pre Tr (W)	Post Tr (W)	Δ (%)	CI 95%	PS t-Test
L1	164.34 (67.60)	187.92 (76.20)	+12.55	LB = −39.70 UB = −11.45	t = −4.99 df = 5 P = **0.004** d = −2.04	95.73 (54.17)	112.38 (63.60)	+14.82	LB = −24.78 UB = −8.51	t = −4.84 df = 7 P = **0.002** d = −1.71	127.02 (85.87)	146.11 (97.06)	+13.06	LB = −29.75 UB = −8.42	t = −4.23 df = 7 P = **0.004** d = −1.49
L2	168.19 (71.12)	210.18 (85.66)	+19.98	LB = −57.91 UB = −26.07	t = −6.78 df = 5 P = **0.001** d = −2.76	113.68 (63.40)	137.81 (74.30)	+17.51	LB = −33.59 UB = −14.66	t = −6.02 df = 7 P = **0.001** d = −2.13	168.44 (88.77)	191.89 (99.34)	+12.22	LB = −33.32 UB = −13.60	t = −5.62 df = 7 P = **0.001** d = −1.99
L3	198.64 (85.04)	214.27 (88.08)	+7.29	LB = −24.36 UB = −6.90	t = −4.60 df = 5 P = **0.006** d = −1.87	125.49 (66.60)	151.73 (78.31)	+17.30	LB = −36.50 UB = −15.98	t = −6.05 df = 7 P < **0.001** d = −2.13	180.41 (109.03)	202.67 (119.17)	+10.99	LB = −32.38 UB = −12.15	t = −5.21 df = 7 P = **0.001** d = −1.84
L4	192.89 (91.97)	221.56 (104.43)	+12.94	LB = −42.37 UB = −14.97	t = −5.378 df = 5 P = **0.003** d = −2.19	100.96 (63.86)	129.65 (78.82)	+22.13	LB = −41.45 UB = −15.94	t = −5.32 df = 7 P = **0.001** d = −1.88	154.15 (102.33)	176.06 (116.63)	+12.45	LB = − −36.11 UB = −7.72	t = −3.65 df = 7 P = **0.008** d = −1.29

L1 = loading 15% 1-RM; **L2** = loading 35% 1-RM; **L3** = loading 65% 1-RM; **L4** = loading 85% 1-RM; **Pre Tr** = Pre Treatment; **Post Tr** = Post Treatment; M (SD); W = Watt. **Δ (%)** = Percentage of variations between pre and post scores (means); **CI95%** = Confidence Interval for the differences; LB = lower bound; UB = upper bound. **PS t-Test** = Paired Samples t-Test; **t** = t values; **df** = degree of freedom; **P** = P values (P values in bold are significant); **d** = Cohen's d values. (Effect Size; ES). Absolute ES of 0.20, 0.50, 0.80, > 1 represent small, medium, large and huge effects, respectively.

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▶ **Table 11** Two way ANOVA [2 (pre-post) x 3 (control and experimental conditions)] - Barbell bench press. Force-velocity loading parameters: within, between-group differences and interactions found in the force values (WB-EMS1 vs. WB-EMS2 vs. CT-MDS) recorded pre and post the different experimental and control treatments.

	Within			Between			Interaction		
	F_{df}	P	$\eta^2_{part.}$	F_{df}	P	$\eta^2_{part.}$	F_{df}	P	$\eta^2_{part.}$
L1	63.354 $_{1,19}$	**<0.001**	0.769	1.143 $_{2,19}$	0.340	0.107	0.307 $_{2,19}$	0.739	0.031
L2	196.145 $_{1,19}$	**<0.001**	0.912	1.553 $_{2,19}$	0.237	0.140	22.319 $_{2,19}$	**<0.001**	0.701
L3	91.106 $_{1,19}$	**<0.001**	0.827	1.710 $_{2,19}$	0.208	0.153	1.239 $_{2,19}$	0.312	0.115
L4	212.991 $_{1,19}$	**<0.001**	0.918	1.496 $_{2,19}$	0.249	0.136	12.994 $_{2,19}$	**<0.001**	0.578

L1 = loading 15 % 1-RM; L2 = loading 35 % 1-RM; L3 = loading 65 % 1-RM; L4 = loading 85 % 1-RM. Two way ANOVA [2 x 3]: F = F values and degrees of freedom; P = P values (P values in bold are significant); η^2_{part} = Partial ETA squared as Effect Size; (ES). Absolute partial ETA squared values < 0.01; 0.01 < η^2_{part} < 0.06; 0.06; < η^2_{part} < 0.14; > 0.14 represent trivial, small, moderate and large effects, respectively.

▶ **Table 12** Two way ANOVA [2 (pre-post) x 3 (control and experimental conditions)] - Barbell bench press. Force-velocity loading parameters: within, between-group differences and interactions found in the Power values (WB-EMS1 vs. WB-EMS2 vs. CT-MDS) recorded pre and post the different experimental and control treatments.

	Within			Between		Interaction			
	F_{df}	P	$\eta^2_{part.}$	F_{df}	P	$\eta^2_{part.}$	F_{df}	P	$\eta^2_{part.}$
L1	64.975 $_{1,19}$	**<0.001**	0.774	1.560 $_{2,19}$	0.236	0.141	0.638 $_{2,19}$	0.539	0.063
L2	121.090 $_{1,19}$	**<0.001**	0.864	1.328 $_{2,19}$	0.289	0.123	4.548 $_{2,19}$	**0.024**	0.324
L3	77.337 $_{1,19}$	**<0.001**	0.803	1.074 $_{2,19}$	0.361	0.102	1.520 $_{2,19}$	0.244	0.138
L4	63.706 $_{1,19}$	**<0.001**	0.770	1.674 $_{2,19}$	0.214	0.150	0.492 $_{2,19}$	0.619	0.049

L1 = loading 15 % 1-RM; L2 = loading 35 % 1-RM; L3 = loading 65 % 1-RM; L4 = loading 85 % 1-RM. Two way ANOVA [2 x 3]: F = F values and degrees of freedom; P = P values (P values in bold are significant); η^2_{part} = Partial ETA squared as Effect Size; (ES). Absolute partial ETA squared values < 0.01; 0.01 < η^2_{part} < 0.06; 0.06; < η^2_{part} < 0.14; > 0.14 represent trivial, small, moderate and large effects, respectively.

tion (≈ 20 min × 12 sessions) in twelve training sessions, compared to about 14 h spent in traditional training (≈ 70 min × 12 sessions). Finally, the WB-EMS training can be useful for people who cannot train with loads because of impairments such as arthritis, cartilage disease tendinopathies.

Moreover, the effectiveness demonstrated by the WB-EMS methods on participants with a high level of fitness appears to be of a practical relevance. In this case, the use of WB-EMS might be a valid alternative or a combination to adopt with more traditional means of training, where the managing of time could be of a certain interest for those professionals involved in a particular period of the season.

Several practical applications from this study have relevance to the strength and conditioning coach. First, these findings demonstrate the highly intense nature of the effects induced by the three different treatments, indicated by the very large effect sizes observed after the training period on the strength and muscle power of all the participants, for each treatment (Cohen's d > 1). Second, we can point out how significant effects can be achieved both by WB-EMS based on 50 and 85 Hz frequencies.

Conclusions

This study suggests that whole-body electrostimulations can be considered as a valid and faster alternative to a traditional overload-based resistance-training program for the development of dynamic strength. Comparing the two different WB-EMS approaches and circuit training, data showed a substantial parity of these methods of training.

Author Contributions

Conceptualization, S.D.; methodology, S.D., G.B. and B.R.; formal analysis, S.D., B.R. and G.B.; investigation, G.B., F.P., A.S., C.C., P.R.G. and A.B..; data curation, B.R. and G.B.; writing—original draft preparation, B.R., G.B., C.R. and S.D..; writing—review and editing, B..R., G.B., C.R. and S.D.; supervision, S.D.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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Comparison of Swim Recovery and Muscle Stimulation on Lactate Removal After Sprint Swimming

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Abstract

Neric, FB, Beam, WC, Brown, LE, and Wiersma, LD. Comparison of swim recovery and muscle stimulation on lactate removal after sprint swimming. *J Strength Cond Res* 23(9): 2560–2567, 2009—Competitive swimming requires multiple bouts of high-intensity exercise, leading to elevated blood lactate. Active exercise recovery has been shown to lower lactate faster than passive resting recovery but may not always be practical. An alternative treatment, electrical muscle stimulation, may have benefits similar to active recovery in lowering blood lactate but to date is unstudied. Therefore, this study compared submaximal swimming and electrical muscle stimulation in reducing blood lactate after sprint swimming. Thirty competitive swimmers (19 men and 11 women) participated in the study. Each subject completed 3 testing sessions consisting of a warm-up swim, a 200-yard maximal frontcrawl sprint, and 1 of 3 20-minute recovery treatments administered in random order. The recovery treatments consisted of a passive resting recovery, a submaximal swimming recovery, or electrical muscle stimulation. Blood lactate was tested at baseline, after the 200-yard sprint, and after 10 and 20 minutes of recovery. A significant interaction ($p < 0.05$) between recovery treatment and recovery time was observed. Blood lactate levels for the swimming recovery were significantly lower at 10 minutes (3.50 ± 1.57 mmol·L^{-1}) and 20 minutes (1.60 ± 0.57 mmol·L^{-1}) of recovery than either of the other 2 treatments. Electrical muscle stimulation led to a lower mean blood lactate (3.12 ± 1.41 mmol·L^{-1}) after 20 minutes of recovery compared with passive rest (4.11 ± 1.35 mmol·L^{-1}). Submaximal swimming proved to be most effective at lowering blood lactate, but electrical muscle stimulation also reduced blood lactate 20 minutes postexercise significantly better than resting passive recovery. Electrical muscle stimulation shows promise as an alternate recovery treatment for the purpose of lowering blood lactate.

Key Words passive recovery, active recovery, H-wave, swimming performance

Introduction

Competitive swimming performance frequently requires a swimmer to complete multiple bouts of high-intensity exercise within 1 meet. Each of these intense exercise bouts results in significant metabolic disturbances. Fuel sources including creatine phosphate and carbohydrates are rapidly consumed, and metabolic products are made, especially lactic acid. The body begins to recover immediately after the exercise bout because fuels are being stored back into the exercised skeletal muscle and the metabolic products are being cleared from the muscle and blood. But full recovery from these metabolic disturbances, including the return of blood and muscle lactate to resting levels, can take up to 60 minutes or more (21,28). It is quite possible that a swimmer will complete 2 or more intense events separated by no more than 30 minutes and thus be unable to sufficiently recover before the next event. There is concern that elevated muscle and blood lactate levels after 1 event, if not reduced to near resting levels before the next event, may negatively affect subsequent performance (3,9).

The high blood and muscle lactate levels resulting from high-intensity exercise can potentially be detrimental to subsequent sports performance for a variety of reasons. Excessive lactate levels can produce a severe burning sensation that some have observed to decrease swimming speed (20). Physiologically, the greatest consequence of lactate production is the associated elevation of hydrogen ion concentration [H^+] and low pH observed in the muscle and blood. The high [H^+] can contribute directly to muscular fatigue by affecting the contractile process. It can reduce the force of contraction by inhibiting calcium release from the sarcoplasmic reticulum or by interfering with the binding of calcium and troponin (10,14,26). This direct action of high [H^+] on the contractile mechanism is important during exercise but is likely less important during recovery. Force production recovers almost

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fully while muscle pH remains depressed during recovery, suggesting that the high [H^+] may indirectly affect performance by impairing energy metabolism (27). Most of the energy required for a 200-yard swimming sprint is supplied by fast anaerobic glycolysis. For maximal performance in this event, it is important that fast anaerobic glycolysis operates at a maximal rate dependent on the full activation of its associated enzymes. However, 2 of the important rate-limiting enzymes in glycolysis, phosphofructokinase and lactic dehydrogenase, are both inhibited by elevated [H^+] (3,4,18,19). If lactate and [H^+] are elevated from a previous sprint, subsequent performance is likely to be diminished in part by the direct effect on the contractile process and indirectly through the inhibition of rate-limiting glycolytic enzymes. Therefore, it follows that removing lactic acid faster during recovery from 1 exercise bout should benefit the performance of any subsequent exercise bouts that rely on glycolytic metabolism such as a 200-yard swimming event (4,17).

The activity performed during the recovery period after intense exercise can impact the rate of lactate removal from the muscle and blood. Active exercise recovery or warm-down has been shown numerous times to speed the removal of blood lactate compared with a passive resting recovery (3,4,7,9,13,21,34). This holds true in a variety of exercise modes including running, cycling, and swimming. In general, active exercise recovery can double the rate of lactate removal, thereby cutting in half the time required for blood lactate to return to near resting levels when compared with passive resting recovery (4,5,7,8,15,21). Faster lactate removal with active exercise recovery is believed to be caused by greater lactate oxidation as an energy source by the exercising muscle (4,5,30). The exercise also maintains a greater skeletal muscle blood flow (12), which may help transport the lactate out of the exercised muscles and distribute it to nonexercised muscles and other tissues throughout the body where it can be used for fuel or converted to glucose and restored back into the muscle (11).

During competitive swimming performance, the preference would be to use a swimming recovery or warm-down between events. However, in cases where there is no pool available for a sufficient swimming recovery, alternative recovery treatments must be sought. Studies have been published on swimmers using active recovery treatments other than swimming, including walking (29), running (7), and rowing (9). These treatments, although affective, may be limited in their practicality or may not be popular with swimmers. Another alternative treatment that has not yet been studied is low-frequency transcutaneous electrical stimulation of large muscles during recovery. The muscular contractions created in response to the electrical stimulation result in a greater energy demand and potentially in greater blood flow and lymphatic drainage in the contracting muscles. Theoretically, this could result in some of the same benefits expected from the active exercise recovery and facilitate faster blood lactate removal. Therefore, the purpose of this study was to evaluate the effectiveness of submaximal swimming recovery and transcutaneous electrical muscle stimulation in promoting blood lactate removal after a maximal effort swim compared with a passive resting recovery.

Methods

Experimental Approach to the Problem

Sprint swimming performance requires a significant contribution from anaerobic energy sources including glycolytic metabolism. A consequence of producing energy by way of glycolytic metabolism is the production and accumulation of muscle and blood lactate. Elevated lactate levels are related to muscular fatigue and potentially to reduced swimming performance. Most sprint and middle-distance competitive swimmers perform multiple bouts of intense exercise over the course of a 2- to 3-hour swimming competition, resulting in the production of significant amounts of lactate. It is important that these swimmers use appropriate recovery methods between events to maximize the clearance of muscle and blood lactate. Previous studies have demonstrated the benefits of an active exercise recovery in reducing blood lactate when compared with a passive resting recovery. There is reason to believe that other types of recovery treatments may also be beneficial in speeding the removal of lactate but have not been studied to the same extent as active exercise recovery. One such recovery treatment is transcutaneous electrical muscle stimulation. The rationale for electrical muscle stimulation speeding the removal of lactate hinges on its ability to create low-frequency submaximal muscle contractions that potentially promote increased blood flow through and lymphatic drainage from the exercised muscle. This investigation was designed to compare the effects of 3 types of recovery treatments, passive resting, active submaximal swimming, and transcutaneous electrical muscle stimulation, on the time course of blood lactate after high-intensity swims. On 3 separate days, swimmers completed a maximal 200-yard frontcrawl sprint and then completed 1 of the 3 recovery treatments in random order. Blood samples were drawn immediately after the sprint and then again at 10 and 20 minutes into recovery to study the effect of the 3 recovery treatments.

Subjects

Thirty competitive swimmers (19 men and 11 women) from high school and collegiate swim teams volunteered for the study. Their mean ($\pm SD$) age, height, and weight were 17.7 $\pm$ 2.9 years, 175.6 $\pm$ 8.8 cm, and 67.4 $\pm$ 10.7 kg, respectively. Participants in this study trained on a year-round basis. Data were collected in May, considered to be 1 to 3 weeks postseason. Swimmers were selected for the study based on their previous swimming performance. Only swimmers who had swum a 200-yard frontcrawl in competition in under 1:53.50 (men) or 2:04.00 (women) at least once in the previous 12 months were selected. These times were the time

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standards for boys' and girls' 200-yard freestyle as identified by the California Interscholastic Federation, Southern Section (6).

The study was approved by the university institutional review board. Swimmers were recruited through age-group swim teams and consisted of high school and community college athletes. All adult subjects signed an informed consent document. All minor subjects signed a minor assent form, and their parent or legal guardian signed a parental consent form before participation.

Procedures

The subjects were tested individually on 3 occasions, each separated by a minimum of 24 hours. All 3 testing sessions were completed within 3 weeks. All subjects were required to wear a swimsuit that exposed the lower extremities 5 to 7 cm inferior to the greater trochanter and exposed the lumbar spine to accommodate the placement of electrodes for the purpose of transcutaneous electrical muscle stimulation.

One complete testing session consisted of the following parts. The subjects began with a 1,200-to 1,500-yard warm-up swim at a self-selected pace followed by a 2-minute passive resting recovery. They then completed a 200-yard maximal frontcrawl sprint begun from a dive followed by a 3-minute resting recovery, after which a blood sample was drawn to determine a "peak" blood lactate value. They then completed 1 of 3 recovery treatments in randomized order. Treatment 1 was a 20-minute seated resting recovery during which subjects sat passively in a chair near the pool deck. Treatment 2 was a 20-minute active recovery during which the subjects swam 100-yard repeats at approximately 65% of their 200-yard sprint speed. Times for the 100-yard repeats ranged from 1:18 to 1:29 for the men and 1:28 to 1:39 for the women. Treatment 3 was a 20-minute session of electrical muscle stimulation. A blood sample was drawn 10 minutes into the treatment session to determine a "mid-recovery" blood lactate value, and a final blood sample was drawn after the 20-minute recovery treatment to determine a "postrecovery" blood lactate value. One "baseline" blood lactate was determined for each subject before the warm-up swim on the first testing day only. This 1 value was used as the baseline for all 3 recovery treatments.

Administration of Electrical Muscle Stimulation

Transcutaneous electrical muscle stimulation was administered using an H-wave Home Model P-4 electrical stimulator (Electronic Waveform Laboratory, Inc., Huntington Beach, CA, USA). The H-wave stimulator is capable of producing a biphasic, exponentially decaying waveform up to a peak current of 35 mA at frequency settings ranging from low frequency (2 Hz) to high frequency (70 Hz). The "intensity" of the signal can be controlled on a 10-point scale ranging from the lowest setting of 0 (0 mA) to the highest setting of 10 (35 mA). According to the manufacturer, low-frequency stimulation (2 Hz) is used to reduce peripheral edema, and high-frequency stimulation (70 Hz) is used to reduce peripheral pain. The low-frequency setting (2 Hz) was selected for use in this study in an attempt to elicit a peripheral muscle pump action by electrically inducing low-tension, nonfatiguing muscle contractions at approximately 10% of maximum voluntary contraction (16,25).

Electrical muscle stimulation was administered primarily to muscles in the region of the anterior thighs and lower back of the subject. These muscles, the rectus femoris, latissimus dorsi, and triceps, were chosen because of their significant involvement in swimming. Electrodes were placed bilaterally at the origins and insertions of the rectus femoris (5 cm inferior to the greater trochanter, midshaft; 5 cm superior to the superior patellar border, midshaft) and latissimus dorsi muscles (posterior aspect of the upper arm, midshaft; 5 cm lateral to the spinous processes of L3 and L4) (Figure 1). Because of the placement of the electrodes on the upper arm at the insertion of the latissimus dorsi, secondary contractions of the triceps were also elicited. With the subject seated in a chair near the pool deck, the H-wave stimulator was set to 2 Hz, and the intensity level was gradually increased until the subject felt a "mild tapping" on their skin or until mild

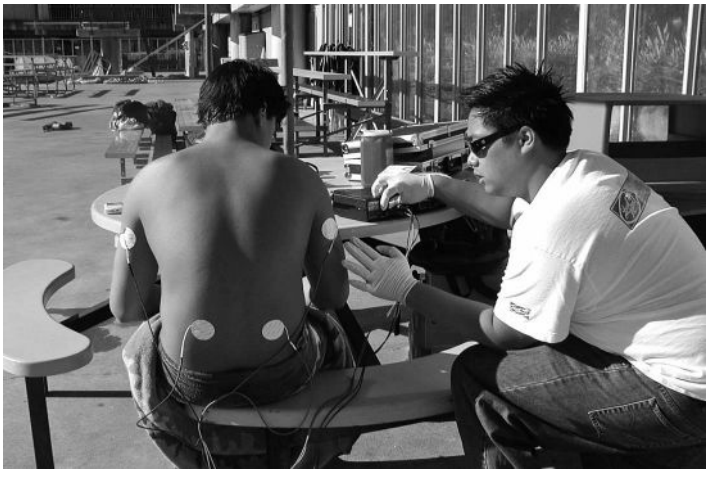

Figure 1. Electrical muscle stimulation was conducted with subjects seated next to pool deck. Visible in photo are surface electrodes placed bilaterally at origins and insertions of latissimus dorsi muscles and H-Wave electrical stimulator.

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muscular contractions were visible. At this point, the intensity was increased further until the subjects felt a "strong, yet comfortable contraction." After 2 to 3 minutes, the subjects often became used to the contractions, and the intensity was increased again (typically to an intensity value of 7–10) to elicit strong yet comfortable contractions.

Determination of Blood Lactate

Blood lactate values were determined using an Accutrend Portable Lactate Analyzer (Boehringer Mannheim, Indianapolis, IN, USA) that was calibrated and operated according to the manufacturer's specifications. A portable analyzer was selected so that blood lactate measurements could be made poolside. The analyzer works by placing a sample of whole blood on a test strip and inserting it into the analyzer for it to react with lactate oxidase. Lactate concentration is then determined from reflectance photometry in the range of 0.7 to 26.0 mmol·L^{-1}. The reliability and validity of the Accutrend analyzer have been reported in previous studies. Pinnington and Dawson (23) showed the analyzer to be reliable (intraclass correlation coefficient [ICC] $r = 0.995$) and to demonstrate good association (ICC $r = 0.853$) with the Analox LM3 analyzer (Analox Instruments, Ltd., London, UK).

Blood samples were drawn either from the posterior-inferior aspect of the earlobe or the lateral aspect of the fingertip midway between the nail plate and the inferior distal phalanx. The sample sites were wiped with isopropyl alcohol swabs and punctured with a spring-loaded lancet device followed by 2 to 3 seconds of a "milking" technique (alternating pressure and release 6–8 mm from the puncture site) to promote blood flow from the wound. Blood droplets approximately 3 mm in diameter were applied directly to the test strips for the determination of blood lactate (mmol·L^{-1}). For subsequent blood samples, if wiping the previous wound with an alcohol swab and milking the area elicited an adequate flow of blood to collect an adequate sample, no further puncture was necessary. However, if the previous site did not yield an adequate sample, a new site was selected and used for subsequent sampling.

Statistical Analyses

Descriptive statistics (mean and *SD*) were calculated for subject characteristics (age, height, and weight) and blood lactate values (by treatment and time). Factorial ($2 \times 3 \times 3$) analysis of variance with repeated measures (ANOVA-RM) was used to test for any main effects, repeated measures effects, or interaction between the differences in blood lactate values between 2 sexes (male and female), 3 recovery treatments (rest, swimming, and electrical stimulation), and 3 repeated times (peak, mid-recovery, and postrecovery). Post hoc analysis of any significant effects identified by the ANOVA-RM was done using one-way ANOVA to compare recovery treatments and repeated times followed up by Scheffé confidence interval procedures. An alpha level of 0.05 was chosen for all statistical comparisons. The statistical analyses were conducted using StatView statistical software (SAS Institute, Inc., Cary, NC, USA).

Results

All subjects were instructed to swim each trial of the 200-yard frontcrawl as fast as possible. The mean (±*SD*) 200-yard swim time for the men was 1:50.0 ± 4.0 seconds and for the women was 2:01.6 ± 3.9 seconds. Both of these mean times are faster than the desired standard times of 1:53.5 and 2:04.0 that were used for recruiting the men and women, respectively. The mean peak blood lactate for all subjects after the 200-yard maximal frontcrawl across all trials was 6.17 ± 2.16 mmol·L^{-1}, ranging from 2.4 to 13.2 mmol·L^{-1}. Analysis of variance revealed no significant ($p = 0.518$) interaction between sex and recovery treatment, and therefore all further statistical analysis was done on the group as a whole regardless of sex. Mean blood lactate values are presented in mmol·L^{-1} (Figure 2) and in relative terms as the percent of remaining blood lactate using the peak blood lactate as the reference (Figure 3).

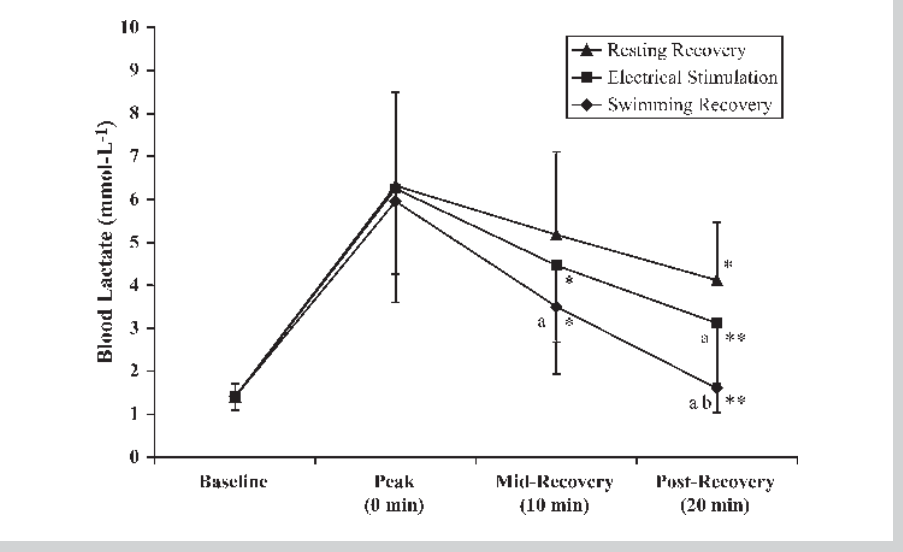

Figure 2. Mean (±*SD*) blood lactate (mmol·L^{-1}) values by recovery treatment. [a]Significantly less ($p < 0.05$) than resting recovery. [b]Significantly less ($p < 0.05$) than electrical stimulation. *Significantly less ($p < 0.05$) than peak. **Significantly less ($p < 0.05$) than mid-recovery.

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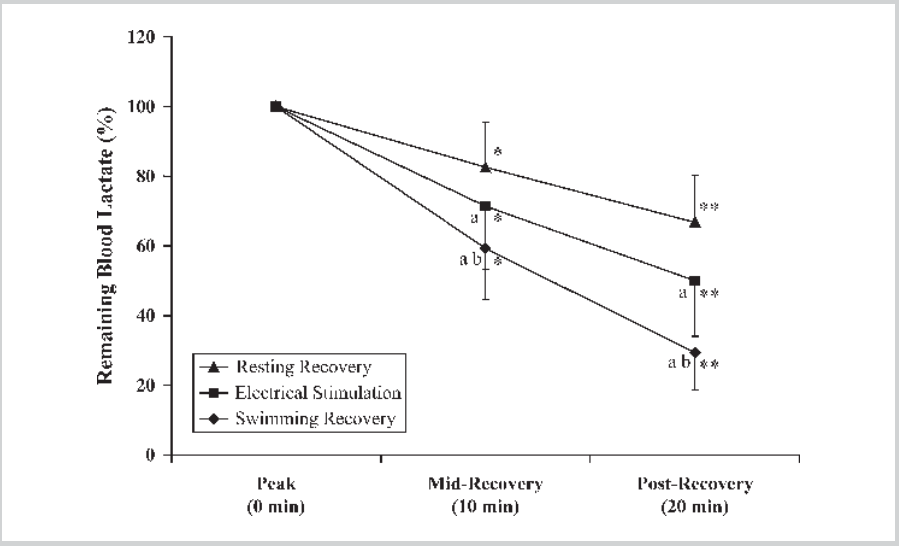

Figure 3. Mean (±*SD*) remaining blood lactate (%) by recovery treatment. [a]Significantly less ($p < 0.05$) than resting recovery. [b]Significantly less ($p < 0.05$) than electrical stimulation. *Significantly less ($p < 0.05$) than peak. **Significantly less ($p < 0.05$) than mid-recovery.

Analysis revealed a significant ($p < 0.05$) interaction between recovery and time for blood lactate (mmol·L^{-1}). A significant drop in blood lactate was observed (Figure 2) with resting recovery from peak (6.32 ± 2.17 mmol·L^{-1}) to postrecovery (4.11 ± 1.35 mmol·L^{-1}). A significant drop in blood lactate was observed with electrical stimulation from peak (6.25 ± 1.99 mmol·L^{-1}) to mid-recovery (4.46 ± 1.79 mmol·L^{-1}) and from mid-recovery to postrecovery (3.12 ± 1.41 mmol·L^{-1}). Similarly, a significant drop in blood lactate was observed with swimming recovery from peak (5.96 ± 2.35 mmol·L^{-1}) to mid-recovery (3.50 ± 1.57 mmol·L^{-1}) and from mid-recovery to postrecovery (1.60 ± 0.57 mmol·L^{-1}). At mid-recovery, blood lactate was significantly lower with swimming recovery (3.50 ± 1.57 mmol·L^{-1}) when compared with electrical stimulation (4.46 ± 1.79 mmol·L^{-1}) and resting recovery (5.18 ± 1.93 mmol·L^{-1}). At postrecovery, blood lactate was significantly lower with both swimming recovery (1.60 ± 0.57 mmol·L^{-1}) and electrical stimulation (3.12 ± 1.41 mmol·L^{-1}) when compared with resting recovery (4.11 ± 1.35 mmol·L^{-1}) and was significantly lower with swimming recovery when compared with electrical stimulation.

Analysis revealed a significant ($p < 0.05$) interaction between recovery and time for remaining blood lactate (%). Remaining blood lactate was significantly lower from peak to mid-recovery and from mid-recovery to postrecovery in all 3 recovery treatment groups (Figure 3). At mid-recovery, remaining blood lactate was significantly lower with electrical stimulation (71.4 ± 18.1%) when compared with resting recovery (82.6 ± 12.9%) and lower with swimming recovery (59.3 ± 14.6%) than both resting recovery and electrical stimulation. The same was true at postrecovery; remaining blood lactate was significantly lower with electrical stimulation (50.1 ± 16.0%) when compared with resting recovery (66.8 ± 13.4%) and lower with swimming recovery (29.5 ± 10.7%) than both resting recovery and electrical stimulation.

Discussion

Mean (±*SD*) blood lactates of all swimmers in this study increased from a baseline value of 1.44 ± 0.34 mmol·L^{-1} to a peak value of 6.17 ± 2.16 mmol·L^{-1} after a 200-yard swim. These values are in close agreement with the results of similar studies by Beckett and Steigbigel (3), who reported a baseline blood lactate of 1.35 ± 0.36 mmol·L^{-1} and peak blood lactates after a 200-yard and 400-yard swim of 7.53 ± 1.67 and 6.86 ± 1.95 mmol·L^{-1}, respectively, and McMaster et al. (21), who reported peak blood lactates of 6.60 ± 1.46 mmol·L^{-1} and 6.45 ± 2.74 mmol·L^{-1} after 200-yard swims. Felix et al. (9) reported slightly lower blood lactates of approximately 1 mmol·L^{-1} at baseline and peak values of approximately 4.2 to 5.3 mmol·L^{-1} after a 200-yard swim in women only. The mean blood lactate after 20 minutes of resting recovery (4.11 ± 1.35 mmol·L^{-1}) was significantly lower ($p < 0.05$) than the peak lactate value but was still significantly elevated over baseline. This value is similar to previous studies that reported blood lactate values of 4.60 ± 1.91 mmol·L^{-1} after 20 minutes (21) and 3.05 ± 1.19 mmol·L^{-1} after 30 minutes of resting recovery (3). It is clear that when swimmers passively rest after a 200-yard swim, blood lactate is still significantly elevated, in some cases above 4 mmol·L^{-1}, for at least 20 to 30 minutes, and may still be elevated above resting levels for over 60 minutes. This elevated blood lactate is believed by many to potentially have a detrimental effect on subsequent physical performance, such that faster and more complete removal of blood lactate after exercise would be particularly beneficial with regard to athletic competition (3,4,9,21,22,31).

Blood lactate was reduced after the 200-yard maximal frontcrawl swim most effectively by using a submaximal swimming recovery (Figure 2). The swimming recovery, modeled after recommendations by McMaster et al. (21), consisted of swimming 100-yard repeats at 65% of each swimmer's maximum 200-yard velocity. Peak blood lactate (5.96 ± 2.35 mmol·L^{-1}) dropped significantly ($p < 0.05$) to 3.50 ± 1.57 mmol·L^{-1} after 10 minutes of recovery, which was significantly lower than with electrical muscle stimulation

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or with resting recovery. It dropped significantly further to 1.60 ± 0.57 mmol·L^{-1} after 20 minutes of recovery, which was again significantly lower than the other 2 treatments. The blood lactate value after 20 minutes of resting recovery was not significantly different ($p = 0.965$) from the baseline value. In terms of the remaining blood lactate, only 29.5 ± 10.7% of the peak lactate value remained after 20 minutes with the swimming recovery, compared with 50.1 ± 16.0% and 66.8 ± 13.4% of lactate remaining for electrical muscle stimulation and resting recovery, respectively (Figure 3). The superior effect of the swimming recovery in reducing blood lactate confirms several previous studies that found similar results with different forms of active exercise recovery. Beckett and Steigbigel (3) found that completion of a 1,000-yard warm-down swim at 60% effort reduced blood lactate more than 30 minutes of sitting on the pool deck (3). McMaster et al. (21) compared the effect of passive recovery to submaximal swimming recovery on blood lactate for 20 minutes after a 200-yard maximal swim. The treatments consisted of sitting on the pool deck or swimming 100-yard repeats at a velocity 65% of the best effort. Similarly to the current study, blood lactate was reduced from a peak value of 6.45 ± 2.74 mmol·L^{-1} to 2.20 ± 1.44 mmol·L^{-1} with the active recovery, compared with a reduction from a peak of 6.60 ± 1.46 mmol·L^{-1} to 4.60 ± 1.91 mmol·L^{-1} after the passive recovery (21). In a follow-up study, the same authors were interested in the effect of exercise intensity during recovery and whether swimming recovery performed at lower intensity (100-yd repeats at 55% of best velocity) or higher intensity (100-yd repeats at 75% of best velocity) had a beneficial effect on lactate clearance. All 3 of the recovery intensities (55%, 65%, and 75% velocity) proved to be effective at lowering blood lactates, with none of the intensities displaying superiority. Subjectively, the swimmers believed the 55% velocity was "too sluggish," the 75% velocity was "too fast," and the 65% intensity was "the best" (22). From the 2 studies combined, it was concluded that recovery swimming at 65% of best effort velocity has important implications for enhancing recovery during competition when repeated performance is required (21,22).

The mode of exercise used during active recovery is also of interest. Denadai et al. (7) studied 3 recovery modes including passive sitting, moderate intensity running, and moderate intensity swimming on lactate removal after 250-m swims at maximal speed with a 2-minute rest in between. Both active recovery conditions removed blood lactate faster than passive sitting, with the running recovery being the most effective treatment. They believed that using an exercise mode for recovery different than the original exercise mode increased the speed of blood lactate removal (7). Felix et al. (9) studied the effect of passive recovery, swimming at 65% of lifetime best velocity in 200-yard freestyle, and rowing at 60% of age-predicted maximal heart rate on blood lactate after a maximal 200-yard swim. Both active recovery modes reduced blood lactate more than passive recovery, with little difference between swimming and rowing recovery. They recommended use of a rowing ergometer as an alternate recovery treatment when swimming recovery was not available during competition (9). Siebers and McMurray (29) compared self-selected rates of swimming recovery and walking recovery and the effect of each on lactate removal after 2 minutes of swimming ergometer exercise. They found that the swimming recovery reduced the lactate concentration by 53.3 ± 3.0% compared with 38.5 ± 3.0% for the walking recovery. No significant difference was found, however, between 200-yard swim times after the swimming and walking recoveries (29). Other studies have also demonstrated that elevated blood lactate levels do not adversely affect subsequent cycling or swimming performance (29,32,33,34). Two of these studies by Toubekis et al. (32,33) found 50-m sprint swimming performance after 6 minutes of recovery from 8 repetitions of 25-m sprints to be unaffected by recovery treatments even when blood lactate levels were significantly different. Swimming performance may have been unaffected partly because of the short sprint distance (50-m) and limited recovery time (6 min), which would place more emphasis on phosphagen metabolism and less emphasis on glycolysis for supplying the energy required for the sprint. Although conflicting evidence exists, it is still logical to believe that elevated blood lactate levels can adversely affect 200-yard swimming performance. Should subsequent research confirm the importance of residual muscle and blood lactate on subsequent performance, then, in addition to facilitating lactate removal, the performance benefits of exercise recovery may also be confirmed.

The ability of active exercise recovery to speed the removal of muscle and blood lactate compared with passive resting recovery is explained primarily by increased lactate oxidation within the exercising muscle (4,5,12,30). Increased blood flow resulting from the exercise recovery may also facilitate lactate transport out of the muscle to other tissues for oxidation or resynthesis to glucose (12,30). Theoretically, a valid alternative to active exercise recovery may be transcutaneous electrical muscle stimulation. Low-frequency electrical stimulation results in strong contractions of large skeletal muscles that should increase the energy demand and promote increased blood flow similar to active exercise recovery. Previous studies using similar stimulation protocols have investigated the effect of electrical muscle stimulation on acute and chronic changes in cardiovascular function and aerobic fitness. Banerjee et al. (2) demonstrated that rhythmic muscle contractions of the quadriceps, hamstrings, gluteal, and calf muscles induced by electrical stimulation at 4 Hz resulted in physiologic responses consistent with light to moderate physical exercise in healthy, sedentary adults. Peak heart rate and oxygen uptake with 3 minutes of electrically induced muscle contractions were 101 ± 12 bpm and 14.9 ± 4.3 ml·kg·min^{-1}, respectively (2). Chronic application of electrical muscle stimulation done for 40 minutes per session, 5 sessions per week, for 6 weeks, resulted in a significant

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aerobic training effect as evidenced by a 10% increase in peak oxygen uptake (1). Poole et al. (24) also showed electrical muscle stimulation at 40 mA acutely increased pulse, blood pressure, energy expenditure, and glucose uptake.

Electrical muscle stimulation during recovery from a 200-yard maximal swim in the current study had a significant effect on blood lactate (Figure 2). From a peak value of 6.25 ± 1.99 mmol·L^{-1}, blood lactate dropped significantly ($p < 0.05$) to 4.46 ± 1.79 mmol·L^{-1} after 10 minutes and dropped significantly again to 3.12 ± 1.41 mmol·L^{-1} after 20 minutes of recovery. At 20 minutes of recovery, the value for blood lactate with electrical stimulation (3.12 ± 1.41 mmol·L^{-1}) was significantly lower compared with passive resting recovery (4.11 ± 1.35 mmol·L^{-1}) but was still significantly higher compared with active swimming recovery (1.60 ± 0.57 mmol·L^{-1}). These results suggest that a passive resting recovery is the least effective treatment for removing blood lactate after a 200-yard swim. When possible, a 20-minute warm-down swim at a velocity 65% of the best 200-yard time would be the preferred recovery treatment because it reduces blood lactate the most. However, if an appropriate warm-down swim is not possible, 20 minutes of electrical muscle stimulation appears to offer a valid alternative treatment option for reducing blood lactate. In addition, other electrical muscle stimulation protocols not yet tested may prove even more effective in reducing blood lactate than the protocol used in this study. Stimulating a greater muscle mass or stimulating at a higher intensity may elicit better results.

Practical Applications

In many sports, including swimming, track and field, and wrestling, competition and training require multiple bouts of maximal intensity exercise resulting in significant physiologic and metabolic disturbances. These disturbances can have detrimental effects on the performance of subsequent heats and events in swimming and track and field and on subsequent matches in wrestling. Ideally, an athlete would like to be fully recovered before competing in another heat, event, or match that requires high-intensity exercise. The potential for being fully recovered is influenced by both the length of time an athlete has to recover between exercise bouts and the activity performed during this recovery period. An athlete who passively rests during recovery, such as sitting in a chair or lying on the ground, will fully recover, but it may take over 60 minutes. When the recovery time between exercise bouts is limited to less than 60 minutes, athletes frequently use an active exercise recovery or other alternate treatments to help speed the rate of recovery. Continuing to actively exercise during recovery has the benefit of using some of the metabolic products made during the intense exercise, especially lactate, as a fuel source. The elevated muscle blood flow maintained by the recovery exercise may also promote the removal of lactate and other metabolic products from the exercised muscles but likely to a lesser degree. An athlete will typically have the ability to exercise recover between competitive events by swimming, stationary cycling, running, or walking. There may be situations, however, in which the athlete has limited access to a pool, stationary bike, or opportunities to run or walk, is physically or psychologically exhausted and not motivated to continue to exercise, or simply seeks an alternate recovery treatment. In these situations, using electrical stimulation to produce strong low-frequency muscle contractions while otherwise resting may be of benefit in helping reduce muscle and blood lactate before subsequent performance.

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Effects of an Electrostimulation Training Program on Strength, Jumping, and Kicking Capacities in Soccer Players

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Abstract

Billot, M, Martin, A, Paizis, C, Cometti, C, and Babault, N. Effects of an electrostimulation training program on strength, jumping, and kicking capacities in soccer players. *J Strength Cond Res* 24(5): 1407–1413, 2010—The present study investigated the influence of a 5-week electrostimulation (EMS) training program on muscular strength, kicking velocity, sprint, and vertical jump performance in soccer players. Twenty amateur soccer players participated in the study, 10 in the electrostimulated group and the remaining 10 in a control group. Electrostimulation was applied on the quadriceps muscles over 5 weeks. Subjects were tested before, during (wk-3), and after (wk-5) the EMS training program. Maximal voluntary contraction using different contraction mode (i.e., eccentric, concentric, and isometric), vertical jump height, sprint running for 10 m, and ball speed were examined. We observed an increase in isometric and eccentric maximal knee extension torques and also a gain in ball speed performance without run up at wk-3. After 5 weeks of EMS training, eccentric, isometric, and concentric torques and ball speed had significantly improved. It appeared *appropriate* to conduct EMS training during at least 3 weeks to observe beneficial effects in specific soccer skills such as ball speed.

Key Words ball speed, knee extensors, isokinetic dynamometer, isometric and eccentric strength

Introduction

Soccer necessitates explosive-type efforts such as tackling, jumping, kicking, and sprinting (32). It has previously been demonstrated that 10-m sprint performance was higher in elite than in amateur soccer players (4,9), and it is generally accepted that muscles of the thigh play an important role in running (35), jumping, and ball kicking (2,14,30). Some studies, such as that of Narici et al. (27), demonstrated a positive correlation between quadriceps maximal voluntary contraction (MVC) and maximal ball velocity. Furthermore, Wisloff et al. (35) reported a positive correlation between maximal squat strength, sprinting, and jumping in elite soccer players. A correlation has also been observed between sprinting and jumping abilities and torque at concentric velocities normalized to subjects' body mass (10). Quadriceps muscles seem important for soccer players. Training of these specific muscles could therefore induce positive modifications in soccer performance.

It has been reported that a 12-week (4 days a week) voluntary isometric training program induced a significant increase in squat jump (SJ)–height performance in young adults (20). In the specific case of soccer, previous studies have found that voluntary strength training improved performance in a specific kicking ball task in soccer (8,11). Therefore, voluntary strength training induces benefits in specific soccer abilities. Among the different training methods, the electrostimulation (EMS) method could improve muscle strength production (5,12,13,21). Indeed, enhancement in strength production was evident in many muscular groups after EMS training ranging from 10 to 41% for quadriceps muscles (3,7,15,16,23,25). Some authors have tested the effects of EMS training on sport performance. After 4 weeks of EMS training on quadriceps and triceps surae muscles, Malatesta et al. (23) reported the positive effects on vertical jump performance in volleyball players. Furthermore, Maffiuletti et al. (23) found that SJ performance in basketball players was improved by 14% after 4 weeks of EMS training on quadriceps muscles. Similarly, it was reported that 3 weeks of EMS on latissimus dorsi and quadriceps muscles decreased stroke and sliding sprint time in swimming and ice hockey, respectively (7,31). On the other hand, Babault et al. (3) measured an increment in squat performance after 6 and 12 weeks of quadriceps EMS training, but observed no significant change on specific scrumming tasks in rugby players.

It thus appeared that EMS training may enhance specific sports movements such as stroke and sliding sprint (3,7,23–25,31),

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whereas improvements in others, such as jump height and sprint time, remain unclear in the literature. To date, no study has investigated the evolution of specific performance in soccer after an EMS training program. Indeed, analysis of the physiological profile of soccer players reveals the importance of anaerobic power in most decisive skills such as jump, sprint, and ball-kicking ability (4). It was also reported that quadriceps femoris muscles are important for specific soccer abilities. Thus, the aim of this study was to test the effects of a 5-week EMS training program on the quadriceps femoris of soccer players. With this intention, strength was measured in different contractile conditions (i.e., isometric, concentric, and eccentric). Moreover, special interest was given to the evaluation of specific soccer tasks such as vertical jump, sprint, and ball speed during kicking. We hypothesized that a 5-week EMS training program on the quadriceps femoris improved muscle strength and sport performance in soccer players.

Methods

Experimental Approach to the Problem

This study was designed to determine the beneficial effects of a 5- weeks EMS training program in soccer players. Strength adaptations were investigated by measuring the isokinetic torque during maximal voluntary eccentric, isometric, and concentric knee extensions. Sport performance adaptations were investigated using ball speed after kicking, vertical jumps, and sprinting. These variables were tested before, 3 weeks (wk-3) and 5 weeks (wk-5) after the beginning of training. Two groups of soccer players were considered. During the 5-week period, the first group (control, C) only followed soccer trainings. The second group (electrostimulated, EMS), in addition to the same soccer training, underwent a 5-week EMS training on the knee extensors. During the 5 weeks, the EMS training program consisted of 3 sessions a week. Statistical analyses allowed us to evaluate the effect of EMS training on physical performances of soccer players. Independent variables were time (before, wk-3, and wk-5) and groups (EMS and C). Values obtained for the different tests were used as dependent variables.

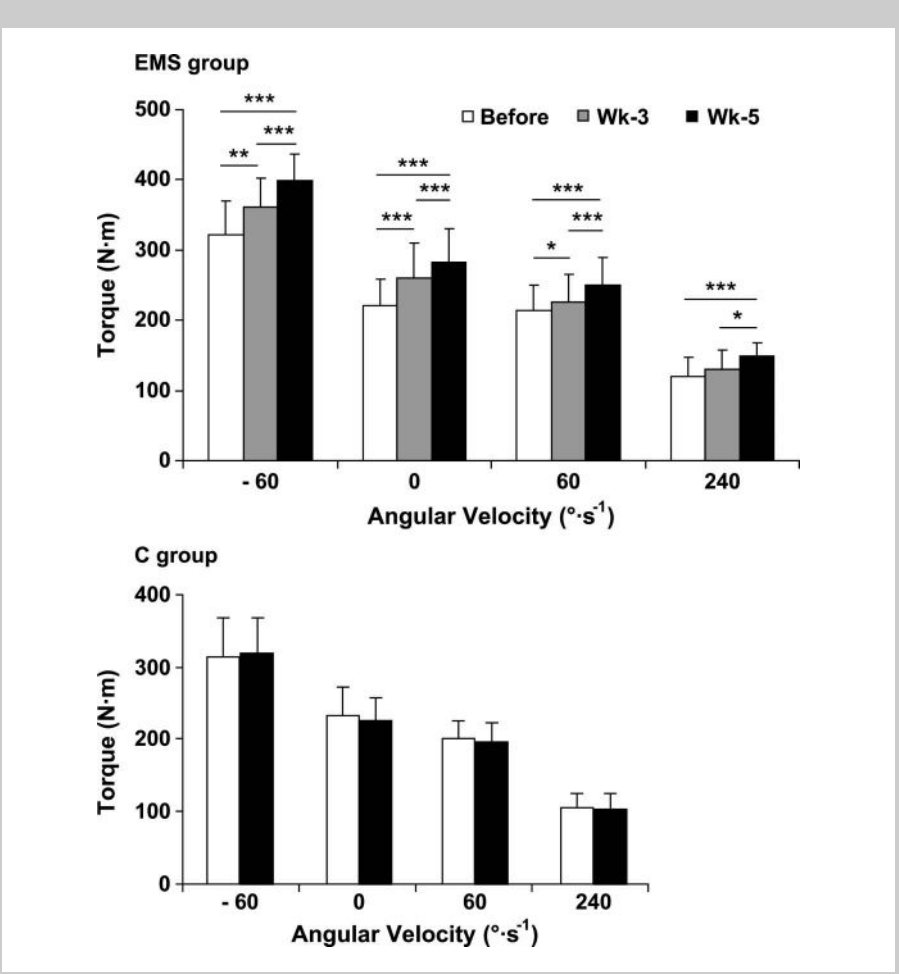

Figure 1. Torque-angular velocity of knee extensors in electrostimulation group and control group. Values measured before and after wk-3 and wk-5 are means ± *SD*. *,**, and ***Significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Subjects

Twenty male soccer players from the faculty of sport science competing at least in the regional division of the French Football Federation voluntarily participated in this study. They were randomly assigned to an electrostimulated group (EMS, $n = 10$; age 20.1 ± 2.1 years; height 1.76 ± 0.06 m; mass 69.5 ± 7.4 kg) or control group (C, $n = 10$; age 21.7 ± 3.4 years; height 1.80 ± 0.05 m; mass 70.7 ± 11.0 kg). All players technically trained twice a week (without physical training) and competed once a week for a total of practical soccer averaging 5 hours a week. They were asked to maintain their usual training, food intake, and hydration. The experiment was conducted during March, corresponding to the last part of the championship. None of them had previously engaged in systematic strength or EMS training. Written informed consent was obtained. All

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experimental procedures conformed to the standards set by the Declaration of Helsinki and were approved by the local Committee on Human Research.

Procedures

The EMS group participated in a 5-week training program that consisted of 12-minute EMS sessions, at a rate of 3 sessions per week. Electrostimulation was performed on both quadriceps femoris muscles. During the stimulation, subjects were seated on a machine used for strength quadriceps strength training (Multi-form, La Roque D'anthéron, France) with the knee fixed at a 60° angle (0° corresponding to the full extension of the leg). A portable battery-powered stimulator (Compex-Energy, Medicompex SA, Ecublens, Switzerland) was used. Three 2-mm-thick self-adhesive electrodes were placed over each thigh. The positive electrodes, measuring 25 cm^2 (5 cm × 5 cm), which had membrane-depolarizing properties, were placed as close as possible to motor points of vastus medialis and vastus lateralis muscles. Negative electrodes, measuring 50 cm^2 (10 cm × 5 cm), were placed near the proximal insertion of rectus femoris muscle. Rectangular wave pulsed currents (100 Hz) lasting 400 μs were used. Electrical stimulation was 3-second long and was followed by a rest period of 17-second (duty cycle 15%). This program was adapted from Compex commercially strength programs. During the training sessions, 36 contractions were performed. Stimulation intensity was determined by the pain tolerance of the subject. The maximally tolerated intensity varied between 60 and 120 mA. The level of force produced by EMS was measured with a myostatic type dynamometer (Allegro, Sallanches, France), and it was verified by the examiner to produce a force higher than 60% of MVC during each training session. For both EMS and C groups, similar soccer training was conducted twice a week.

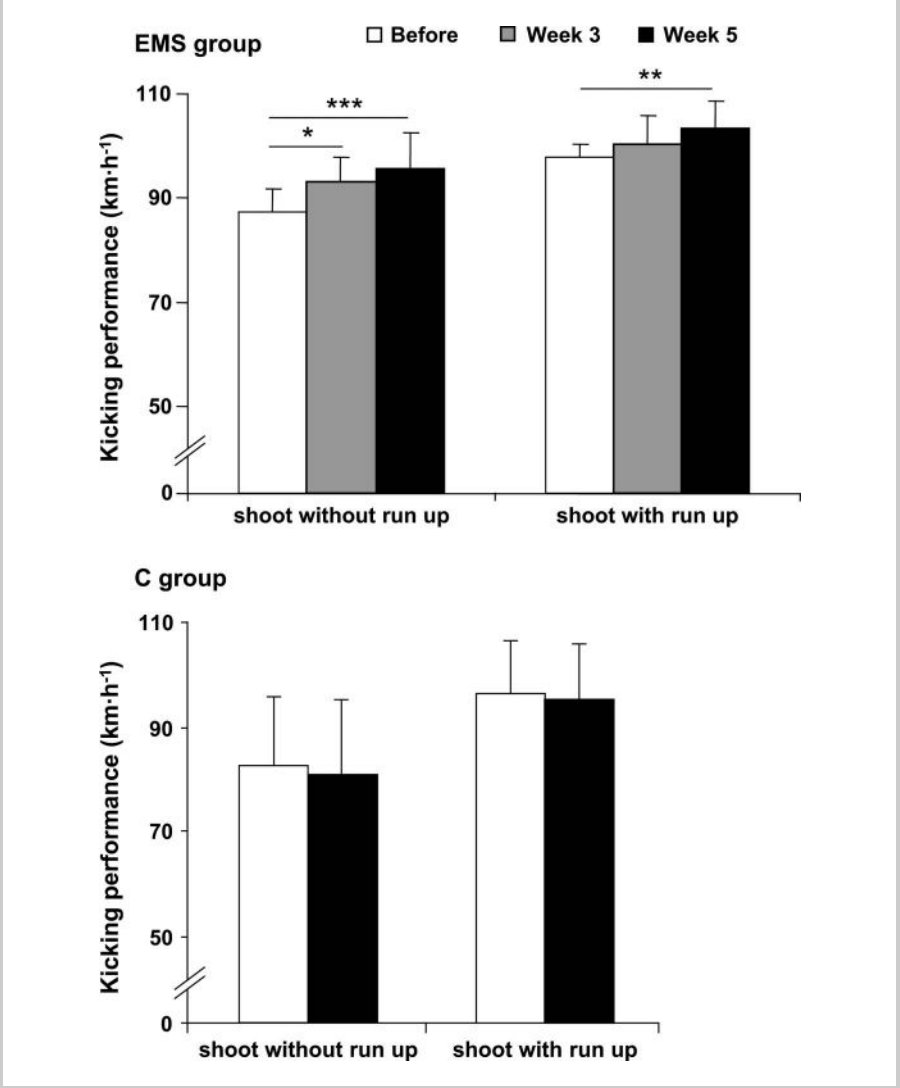

Figure 2. Ball speed during soccer kicking in electrostimulation group and control group. Measured values before and after a wk-3 and a wk-5 period are means ± *SD*. *,**, and ***Significant difference between before, wk-3, and wk-5 at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

Testing

Strength Tests. Tests were performed before and after a 3-week (wk-3) and 5-week (wk-5) period. We used an isokinetic dynamometer (Biodex Corporation, Shirley, NY, USA) to test the strength of the dominant leg (i.e., kicking leg) of each subject. The reliability of strength measurements of the isokinetic dynamometer was previously validated (34). Before the test, a warm-up was carried out by means of 2 series of 10 concentric actions ($30°·s^{-1}$) with increasing intensities. Subjects were seated with the hip at a 90° angle. To minimize hip and thigh motion during the contractions, straps were applied across the chest and pelvis and at midthigh. Another strap secured the leg to the Biodex lever arm, and the alignment between the center of rotation of the dynamometer shaft and the axis of the knee joint was checked at the beginning of each trial. The arms were positioned across

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the chest with each hand clasping the opposite shoulder. Strength measurements consisted of 2 series of 4 consecutive maximal knee extensions and flexions from 90° of flexion to full extension (0°). Contractions were performed at 3 *randomized* angular velocities (concentric: +60 and +240°·s^{-1}; and eccentric: −60°·s^{-1}), then 3 MVCs were performed in isometric conditions at 60°. A 3-minute rest period was allowed between series to eliminate the effects of fatigue. The peak torque was directly measured by the Biodex software. For each condition, only the best trial was included in the analysis. Torques were gravity corrected at each joint angle, using the resistive torque of the weight of the limb obtained at the joint angle where the gravity effect was greatest.

Kicking Tests. Kicking performance was determined from maximal ball speed during shots. The speed, was measured with 44 Check Speed Radars (Tibar Industries, Downview, Ontario, Canada). Check Speed Radars operate with 10.25-GHz frequency, and the frame of the signal is approximately 60° vertical by 40° horizontal. Radars were positioned in both upper and lower corners, behind the goal. This goal was materialized on a net by means of an adhesive strip (3 m wide and 2 m high). The soccer ball was placed at a distance of 9 m. For speed values, we retained speed from the radar nearest the ball impact. The ball characteristics were in accordance with Fédération Internationale de Football Association approval (size: 5, weight: 440 g, circumference: 69 cm, and pressure: 1,000 g·cm^{-2}), and the pressure was verified before each testing session. Shots were effectuated using the dominant leg without run-up (one step before kicking) and with run-up (3 steps before kicking). The best of 3 trials was analyzed for each subject.

Vertical Jump Tests. Each subject performed vertical jumps on an Optojump system (Optojump, Microgate, Bolzano, Italy). A digital timer was connected to the system to measure the flight times of the jumps. The SJ was measured starting from a static semisquatting position (knee angle 90°) and without any preliminary movement. The countermovement jump (CMJ) was performed starting from a standing position, then squatting down to a knee angle of 90 ± 5° and then extending the knee in one continuous movement. During these tests, the arms were kept close to the hips to minimize their contribution. The third jump was a CMJ in which the movement of the arms was free (CMJf). The position of the upper body was also controlled so as to minimize trunk flexion and extension. Subjects were asked to jump as high as they could 3 times, and the best performance was reported.

Sprint Test. Subjects performed 3 10-m sprints, separated by 3-minute recovery periods. Speed was measured with infrared photoelectric cells positioned at 1 m from the floor and 10 m from the start line and controlled by TAC (Test Atletici Computerizzati, TEL.SI. s.r.l. Vignola, Italy) software. After a visual signal, the players started from a standing position and ran the 10-m distance as fast as possible. Performances did not include reaction time. The fastest of 3 trials was used for subsequent analysis.

Statistical Analyses

Standard statistical techniques were used to calculate means and *SD*s. A 2-way analysis of variance (group × time) with repeated measures was used to compare MVC, jump height, sprint, and ball speed. When significant effects occurred, Tukey post hoc analyses were used to test significant differences among values. Statistical power values were calculated for various significant differences. The level of significance was set at $p \leq 0.05$ for all procedures. All statistical tests were performed with Statistica software (version 6.1, StatSoft, Tulsa, OK, USA).

Results

Reliability of measurement showed that the statistical power values for various significant differences ranged from 0.64 to 0.99.

Before training, EMS and C groups were similar in physical characteristics, knee extensor strength, ball speed, vertical jump, or sprint performance ($p > 0.05$). No significant time effect was observed for the C group in all tests ($p > 0.05$).

Concerning the EMS group, eccentric torque increased significantly at wk-3 (+11.5 ± 10.4%, $p < 0.01$) and wk-5 (+22.1 ± 16.4%, $p < 0.001$) as compared with before. A further increase was observed from wk-3 to wk-5 (+9.6 ± 8.1%, $p < 0.01$) (Figure 1). A similar significant increase was obtained in isometric conditions from before to wk-3 and wk-5 (+16.3 ± 21.3, $p < 0.01$ and +27.1 ± 22.6%, $p < 0.001$, respectively) and from wk-3 to wk-5 (+9.2 ± 7.4%, $p < 0.05$). We observed no significant increment between before and wk-3 for both concentric conditions. However, we observed a significant increment between before and wk-5 (+14.0 ± 9.9% at 60°·s^{-1} and +23.2 ± 18.9% at 240°·s^{-1}, $p < 0.001$)

Table 1. Vertical jump performance during SJ, CMJ, and CMJf in EMS and C groups, mean values ± *SD*.*

	SJ (cm)	CMJ (cm)	CMJf (cm)
EMS group			
Before	32.0 ± 6.4	35.1 ± 6.5	40.9 ± 6.1
wk-3	31.7 ± 5.9	33.7 ± 6.3	39.7 ± 6.1
wk-5	33.1 ± 6.2	35.9 ± 5.9†	41.6 ± 5.1
C group			
Before	29.7 ± 4.4	34.4 ± 4.7	40.5 ± 5.8
wk-5	29.3 ± 4.1	33.9 ± 4.8	40.8 ± 5.8

*SJ = squat jump; CMJ= countermovement jump; CMJf = countermovement jump free; C = control; EMS = electrostimulation.

†Significant difference between wk-3 and wk-5 ($p < 0.05$).

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Table 2. Sprint time and velocity at 10 m in EMS and C groups before, after wk-3, and after wk-5.*

	10-m Sprint time (s)	Velocity at 10 m ($m \cdot s^{-1}$)
EMS group		
Before	1.91 ± 0.06	6.83 ± 0.37
wk-3	1.91 ± 0.07	6.95 ± 0.56
wk-5	1.90 ± 0.05	6.83 ± 0.29
C group		
Before	1.91 ± 0.06	7.24 ± 0.70
wk-5	1.93 ± 0.07	7.37 ± 0.61

*EMS = electrostimulation; C = control.
Values are means ± *SD*.

and from wk-3 to wk-5 (+10.0 ± 9.6% at $60° \cdot s^{-1}$ and +14.2 ± 16.5% at $240° \cdot s^{-1}$, $p < 0.01$). Our measurements showed that ball speed without run-up improved significantly at wk-3 (+6.6 ± 8.7%, $p < 0.05$) and wk-5 (+9.6 ± 10.6%, $p < 0.001$) compared with measurements taken before the program. Ball speed with run-up improved significantly at wk-5 (+5.6 ± 4.0%, $p < 0.05$) (Figure 2).

For jump performance, we observed a significant increase from wk-3 and wk-5 in CMJ condition for the EMS group (+6.7 ± 6.3%, $p < 0.05$) (Table 1). However, no significant difference was observed in SJ, CMJ, and CMJf conditions at wk-3 or wk-5 compared with before. Moreover, no significant time effect was observed *either* in sprint time *or* velocity after the wk-3 and wk-5 period in either group (Table 2).

Discussion

The main finding of this study was that in addition to the well-known strength increase, EMS training could lead to benefits in more specific attributes such as kicking speed, with and without run-up. However, strength gains were not directly transferable to jumping ability or sprint performance in our soccer players.

The results of the present study showed smaller strength increases than those previously observed in elite ice hockey players in eccentric conditions (12 vs. 24% in soccer players and ice hockey players, respectively) after 3 weeks of EMS training (7). However, these authors also found a significant increase in the C group and explained gains in eccentric conditions by noting the fact that subjects were more accustomed to performing isokinetic contractions at pretests. Furthermore, it was suggested that fast-twitch fibers might be preferentially recruited during eccentric submaximal contractions (22,33) and that total recruitment may take place during eccentric maximal contractions (19). In addition, Jubeau et al. (19) reported that EMS contractions may result in neither motor unit recruitment according to Henneman's size principle nor in a reversal in this voluntary recruitment order. Thus, a random recruitment of motor units during EMS training may activate easily fast fibers in comparison with voluntary contraction during submaximal level of force. In our study, we suggested that eccentric adaptations may be because of the result of motor unit recruitment. In fact, Nardone et Schieppati (26) reported a greater fast MUs recruitment during eccentric contraction.

The enhancements we observed in isometric conditions corroborated the existing literature. For example, Gondin et al. (16) observed an increment of 15% in the isometric MVC of quadriceps muscles after 4 weeks of EMS training. Early progress in strength production after wk-3 in isometric but not in concentric conditions may be explained by the fact that the angular position during EMS sessions was the same as the isometric test position (i.e., 60°) (16). We also observed that 2 additional weeks of EMS training induced significant enhancements in MVCs in eccentric, isometric, and concentric conditions. We would suggest that benefits observed after 3 and 5 weeks of EMS training were mainly because of neural adaptation. Indeed, it has been previously reported that adaptations observed after 4 weeks of EMS training on quadriceps muscles were mainly because of neural adaptations, whereas changes in muscle mass and architecture became significant between the fourth and the eighth weeks (16). However, our measurements could not confirm these previous adaptive mechanisms.

Research dealing with EMS training and kicking has until now not been undertaken. This study reported an increase in kicking performance without run-up after 3 weeks of EMS training on the quadriceps muscle. Increments were higher and significant after 5 weeks of EMS training in both conditions (with and without run-up). We can thus suggest that strength improvements are transferable to a specific movement such as kicking in soccer players. This finding confirms that quadriceps muscles play an important role during kicking movements (2,28–30). Other studies have found that EMS training could improve specific movements in sports. Indeed, a beneficial effect in swimming sprint and skating performance has previously been reported after 3 weeks of EMS training on latissimus dorsi and quadriceps muscles, respectively (7,31). Conversely, Babault et al. (3) found no improvement in a scrumming task after 6 weeks of EMS training in elite rugby players. These authors explained that the lack of gains in the scrum test may be partly attributed to technical and motivational factors. Technical considerations cannot, therefore, be excluded from criteria of specific performance. Our results, therefore, suggest that EMS training appears to be a viable approach for developing specific attributes used in soccer.

We observed no significant increase in vertical jump performance after 3 or 5 weeks of our EMS training program. These results were in contradiction with Maffiuletti et al. (23) who observed an increment of 14% in SJ after 4 weeks of

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EMS training on quadriceps femoris. These different results could be explained by the fact that fewer contractions were performed in our study for each training session. However, some previous studies were in accordance with our results and reported no significant increase in vertical jump performance. In fact, Malatesta et al. (25) and Herrero et al. (17) reported no significant increase in SJ and CMJ after 4 weeks of EMS training on knee extensors. In addition, a decrease in jumping ability after 3 weeks of EMS training in ice hockey players has been reported (7). The lack of increment or even decline in vertical jump performance might be explained by fatigue or overtraining induced by short EMS training programs. Some studies have reported that a recovery period after EMS or resistance training is necessary to allow an enhancement in jumping performance (1,23–25). Furthermore, it has been previously demonstrated that SJ and CMJ involve not only knee extensor muscles but also plantar flexors (6,18). In this way, Malatesta et al. (25) found a significant increase in mean height during consecutive CMJs after 4 weeks of EMS training of the quadriceps femoris and triceps surae muscles. An increment in jump performance may therefore necessitate training of more than just the quadriceps femoris muscles. It has also been previously reported that EMS training coupled with specific training such as plyometric training induced gains in jump ability (17). Indeed, plyometric training solicits quadriceps muscles in the same way as jumping. Thus, an increase in strength production of quadriceps muscles by EMS and the specificity of plyometric training could induce an enhancement in jumping ability.

Electrostimulation training induced adaptations on explosive type movements such as sprint performance. In this study, sprint time and velocity at 10 m did not change significantly after 3 and 5 weeks of EMS training. These findings are contradictory to those of a previous study. Indeed, Herrero et al. (17) reported a significant improvement in 20-m sprint performance after 4 weeks of EMS training on quadriceps muscles. The lack of gain in sprint performance in our study could be explained by the complexity of the running task in which many muscles are involved and by the technical level of the amateur soccer players tested here. The transfer of strength gains after EMS training appeared more difficult for nonspecific sport performance (i.e., vertical jump and sprint) than specific sport performance (i.e., kicking) in soccer players.

Practical Applications

In summary, soccer necessitates not only technical and strategic training, but also physical conditioning. Three weeks of EMS training programs seems appropriate to improve knee extensors muscle strength in eccentric and isometric conditions in soccer players. However, 2 additional weeks appears necessary to observe increments in all contractile conditions. Moreover, EMS training leads to an improvement in specific soccer tasks such as ball speed performance after kicking. Exclusive EMS training of the quadriceps femoris muscles may be of limited value for improving jumping performance in amateur soccer players. However, some of the following might provide a significant training effect for jumping including (a) the concurrent training of the triceps surae, gluteus maximus, and hamstrings, (b) the inclusion of an optimal recovery period, and (c) the coupling of EMS training with plyometric training. Additionally to traditional soccer training, an EMS training program of 3- or 5-week period appears *to represent a viable means for improving* force and specific soccer tasks at preseason and during the season. In fact, this original method might be used to complement traditional training for soccer. It would infuse variability into the training program, which might enhance the motivation of some players. Furthermore, EMS might also be used for injured athletes to attenuate or eliminate detraining effects.

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Effects of Three Recovery Protocols on Range of Motion, Heart Rate, Rating of Perceived Exertion, and Blood Lactate in Baseball Pitchers During a Simulated Game

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Abstract

Warren, CD, Szymanski, DJ, and Landers, MR. Effects of three recovery protocols on range of motion, heart rate, rating of perceived exertion, and blood lactate in baseball pitchers during a simulated game. *J Strength Cond Res* 29(11): 3016–3025, 2015–Baseball pitching has been described as an anaerobic activity from a bioenergetics standpoint with short bouts of recovery. Depending on the physical conditioning and muscle fiber composition of the pitcher as well as the number of pitches thrown per inning and per game, there is the possibility of pitchers fatiguing during a game, which could lead to a decrease in pitching performance. Therefore, the purpose of this study was to evaluate the effects of 3 recovery protocols: passive recovery, active recovery (AR), and electrical muscle stimulation (EMS) on range of motion (ROM), heart rate (HR), rating of perceived exertion (RPE), and blood lactate concentration in baseball pitchers during a simulated game. Twenty-one Division I intercollegiate baseball pitchers (age = 20.4 ± 1.4 years; height = 185.9 ± 8.4 cm; weight = 86.5 ± 8.9 kg; percent body fat = 11.2 ± 2.6) volunteered to pitch 3 simulated 5-inning games, with a maximum of 70 fastballs thrown per game while wearing an HR monitor. Range of motion was measured pre, post, and 24 hours postpitching for shoulder internal and external rotation at 90° and elbow flexion and extension. Heart rate was recorded after each pitch and after every 30 seconds of the 6-minute recovery period. Rating of perceived exertion was recorded after the last pitch of each inning and after completing each 6-minute recovery period. Immediately after throwing the last pitch of each inning, postpitching blood lactate concentration (PPLa−) was measured. At the end of the 6-minute recovery period, before the next inning started, postrecovery blood lactate concentration (PRLa−) was measured. Pitchers were instructed to throw each pitch at or above 95% of their best-pitched fastball. This was enforced to ensure that each pitcher was throwing close to maximal effort for all 3 simulated games. All data presented represent group mean values. Results revealed that the method of recovery protocol did not significantly influence ROM ($p > 0.05$); however, it did significantly influence blood lactate concentration ($p < 0.001$), HR ($p < 0.001$), and RPE ($p = 0.01$). Blood lactate concentration significantly decreased from postpitching to postrecovery in the EMS recovery condition ($p < 0.001$), but did not change for either the active ($p = 0.04$) or the passive ($p = 0.684$) recovery conditions. Rating of perceived exertion decreased from the postpitching to postrecovery in both the passive and EMS recovery methods ($p < 0.001$), but did not decrease for AR ($p = 0.067$). Heart rate decreased for all conditions from postpitching to postrecovery ($p < 0.001$). The use of EMS was the most effective method at reducing blood lactate concentration after 6 minutes of recovery during a simulated game (controlled setting). Although EMS significantly reduced blood lactate concentrations after recovery, blood lactate concentrations after pitching in the simulated games were never high enough to cause skeletal muscle fatigue and decrease pitching velocity. If a pitcher were to throw more than 14 pitches per inning, throw more total pitches than normal per game, and have blood lactate concentrations increase higher than in the simulated games in this study, the EMS recovery protocol may be beneficial to pitching performance by aiding recovery. This could potentially reduce some injuries associated with skeletal muscle fatigue during pitching, may allow a pitcher throw more pitches per game, and may reduce the number of days between pitching appearances.

Key Words active recovery, electrical stimulation recovery, passive recovery

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Introduction

The act of baseball pitching has been described as a high-intensity anaerobic activity from a bioenergetics standpoint with short bouts of recovery (3,27,28). Depending on the physical conditioning and muscle fiber composition of the pitcher as well as the number of pitches thrown per inning and per game, there is the possibility of pitchers fatiguing during a game, which could lead to a decrease in pitching performance. Since the competitive performance on the field is of the utmost importance to players, coaches, and owners of professional teams, it makes sense that sports science should be evaluating ways to enhance baseball pitching performance as well as ways to recover before the next required pitching performance. Unfortunately, because there is still a lack of research evaluating physiological aspects of recovery in pitching, pitchers are throwing in competitive situations as a starting pitcher (pitching every fourth or fifth day), as a middle relief pitcher (pitching every other day), or as a closing pitcher (pitching at the end of most games) and may not have appropriate recovery between pitching appearances based on the needs of the team or the injuries on a team. Although this may be happening, could recovery be addressed in another way? What if we had the ability to physiologically aid recovery between innings, which may assist the pitcher during the game they are throwing and possibly help them feel better before their next pitching performance? For baseball pitchers, this could mean being able to perform at optimal levels consistently. This could lead to more wins, better "arm health," and ultimately, more money for the respective pitcher.

Periodization of training has been found to be an effective method of training athletes (8,47). This method of designing training programs requires that appropriate rest periods to be implemented to enhance performance (14,33). Because pitchers have an undetermined period of rest between each pitch and each inning due to the nature of the game, it is impossible to effectively implement appropriate rest periods during actual pitching appearances. Therefore, baseball coaches have attempted to decrease the stress on the starting pitcher's arm and body by implementing a 100–120 pitch count. This means that a starting pitcher will be removed from the game when they accumulate total pitches thrown in this range. Ironically, despite the introduction of the 100–120 pitch count and the increased use of relief pitchers, the injury rate of pitchers has continued to increase (21,23,26).

Hackney found that the overhead throwing athlete is prone to injuries, which differ from those of the nonthrowing population because the shoulder is at its most vulnerable point during the late cocking and follow through phases of the throwing motion (13). Because baseball pitching is a high-intensity, repetitive, ballistic motion that can cause muscle fatigue, the muscles of the throwing shoulder can experience a loss of control during the pitching process (13,36). This fatigue can contribute to decreases in the function of the sensorimotor system and can lead to abnormal movement of the humeral head (4,11,22,34,37,40,41). The functional fatigue of the sensorimotor system may lead to greater stresses being placed on the static and dynamic joint stabilizer muscles due to the angular velocities and forces produced during the pitching motion (29,37,41). Additionally, Reinold et al. (29) reported that baseball pitching has acute effects on ROM and implied that the change in ROM may determine the potential for injury.

Most recently, Warren et al. (46) evaluated 3 methods of recovery on baseball pitchers. They reported that blood lactate concentrations were reduced between innings when electrical muscular stimulation was used as a treatment recovery. However, one of the limitations of this study was that the mean prepitching blood lactate concentration for the pitchers before using the electrical muscular stimulation treatment recovery was higher than the other 2 prepitching blood lactate concentrations. Had these resting prevalues been similar to the other prepitching blood lactate values (passive and active recovery [AR] treatment games), which would be expected because the same pitchers were throwing all 3 simulated games with the same number of days of rest between pitching performances, it is speculated that there would not have been a significant difference in postpitching blood lactate concentration (PPLa−) for the pitchers using the electrical muscular stimulation treatment recovery. However, it was stated in the article that the pitchers in the study did prefer the electrical muscular stimulation to passive and AR methods.

Several strategies to facilitate recovery have been investigated in the literature, including AR, passive recovery (PR), and electrical muscular stimulation. Passive recovery is simply rest, often in the form of sitting, lying down, or stretching. Typically, 15–25 minutes of rest is thought to be the optimal time for returning pH levels to normal after performing moderate intensity exercise (5). This form of recovery has the ability to allow the body to maintain and restore its glycogen stores due to its inactive method (4). Passive recovery, in some studies, has shown to have the same effect of lowering blood lactate concentrations as AR, but without the energy expenditure (6,30,39).

Active recovery, wherein athletes participate in low-to-moderate intensity active movement, often cardiovascular in nature in an effort to increase blood flow, has been shown in previous studies to be an effective form of recovery (1,5,6,9,25). The rationale for AR is to allow vasodilatation and oxygen-rich blood to increase the rate of blood lactate clearance in the muscle (1,6,25,48). It has been found that the best AR has come from activity ranging from a progressive decline in intensity of 60–30% of the estimated maximum heart rate (HR) of the exercising person (13,25,32).

Electrical muscle stimulation (EMS), which is a relatively new modality for postexertional recovery, has received very little attention in the literature. It is based on the principle

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that EMS induces muscle contraction with corticospinal excitation, which would increase blood flow thereby reducing lactic acid build up. Studies have shown that EMS increases blood flow more than when voluntary muscle exercises are used (15,31,32,42,45). This increase of blood flow has been shown to help reduce the lactic acid build up (31,32). The theoretical advantage of EMS is that focal muscle stimulation can increase blood flow without accelerating the HR and without increasing arterial blood pressure (2,24,43,45). Thus, muscle contractions occur without cardiovascular strain or mental fatigue (7).

Presently, there is little evidence to support the use of 1 recovery method over another between innings while pitching in a baseball game. Therefore, the purpose of this study was to evaluate the effects of 3 recovery protocols on range of motion (ROM), HR, rating of perceived exertion (RPE), and blood lactate concentrations in baseball pitchers during a simulated game.

Methods

Experimental Approach to the Problem

Baseball pitching performance requires a significant contribution from anaerobic energy sources including glycolytic metabolism. A consequence of producing energy by way of glycolytic metabolism is the production and accumulation of muscle and blood lactate. Elevated blood lactate concentration is related to muscular fatigue and if this occurs for a baseball pitcher, this could potentially negatively affect pitching performance. Most college pitchers throw an average of 14 pitches per inning (27). If they throw numerous innings, pitch counts for a starting pitcher could accumulate to 100–120 pitches per game. The duration of a baseball game is between 2.5 and 3.5 hours, depending on the number of runs scored by both teams. It is thought that pitchers might accumulate blood lactate when they throw more pitches per inning than normal or not have enough time to clear any accumulated blood lactate if the rest time between innings is less than normal. Both of these situations could negatively affect pitching performance or the ability to pitch again with a short number of days between pitching performances. It is important that these pitchers use appropriate recovery methods between innings to maximize the clearance of muscle and blood lactate. Previous studies have demonstrated the benefits of an active exercise recovery in reducing blood lactate when compared with a passive resting recovery for swimmers. There is reason to believe that other types of recovery treatments may also be beneficial in speeding the removal of lactate but have not been studied to the same extent as AR in baseball pitchers. One such recovery treatment is transcutaneous EMS. The rationale for EMS speeding the removal of lactate hinges on its ability to create low-frequency submaximal muscle contractions that potentially promote increased blood flow and lymphatic drainage from the exercised muscle. This investigation was designed to compare the effects of 3 types of recovery treatments; PR, AR, and EMS on blood lactate concentrations while throwing a simulated game. Blood samples were drawn immediately after each pitched inning and then again at the end of the 6-minute recovery protocol between innings to study the effect of the 3 recovery methods. On 3 separate days, with 4 days of recovery between simulated games, pitchers threw 14 pitches per inning for 5 innings while they randomly completed 1 of the 3 recovery protocols after every inning. Additionally, ROM of the shoulder and elbow were measured pre, post, and 24 hours postpitching. Heart rate was recorded after each pitch and every 30 seconds during the 5-minute and 6-minute recovery protocols of each simulated game. Rating of perceived exertion was recorded immediately after throwing the last pitch for each inning and after completing each of the 6-minute recovery protocols.

Subjects

Twenty-one Division I intercollegiate baseball pitchers (starting pitchers = 8 and relief pitchers = 13) volunteered for this study. Their mean ($\pm SD$) age, height, weight, and percent body fat were 20.4 ± 1.4 years, age ranges were 19–24 yr; 185.9 ± 8.4 cm, 86.5 ± 8.9 kg, and 11.2 ± 2.6%, respectively. Their mean ($\pm SD$) number of years playing baseball and playing college baseball was 14.5 ± 2.8 and 2.7 ± 1.1 years, respectively. Data were collected in November and January after fall baseball practice had ended. Pitchers were well trained, had pitched the entire fall, and were selected for the study based on their health. Each participant had undergone and passed a physical performed by team doctors. At no time during this study were any participants under any medical supervision for conditions that would not allow for the normal biomechanics of a pitch (i.e., physical therapy, pre- or postsurgery within a year). The study was approved by the Institutional Review Board of A.T. Still University. All subjects signed an informed consent document before participation.

Procedures

All participating pitchers received comprehensive instruction and demonstrations of the testing procedures before the initiation of the study. The subjects were tested individually on 3 occasions, each separated by 4 days of rest. The 3 in-between inning recovery protocols were randomly assigned to each pitcher to avoid any pitching fatigue effect or perceptions about the recovery treatments. All 3 testing sessions were completed outside during the off season, within 12 days at the respective university's baseball stadium. All subjects were required to wear their normal practice attire while wearing spikes and pitching from a bull-pen mound. Pitchers were instructed to eat and drink "normally" during the testing sessions to maintain their nutritional and hydration status.

One complete testing session consisted of the following parts. The subjects began 30 minutes before pitching the simulated game by drinking 16 oz of water and sitting quietly for 5 minutes to obtain resting or "baseline" HR and blood

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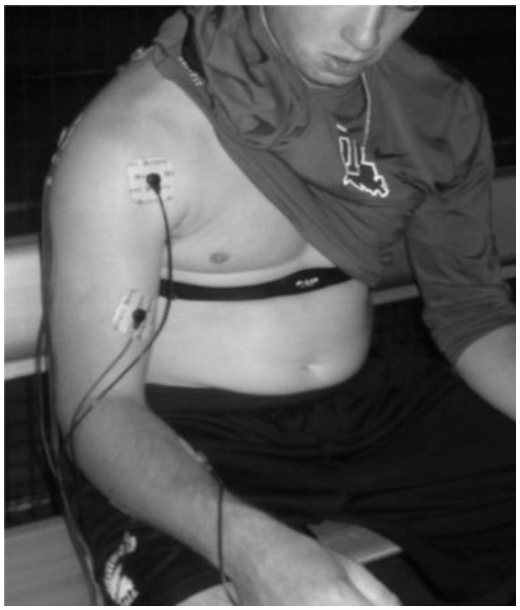

Figure 1. EMS pad placement.

lactate concentration. Then, pitchers had their baseline ROM of their shoulder and elbow assessed. Once the baseline data were measured and recorded, pitchers were told to perform their normal pregame warm-up that consisted of jogging at low intensity for 8–10 poles (from left field to right field lines), followed by an active, dynamic upper- and lower-body warm-up. Once this was completed, pitchers played catch for 10–15 minutes (the number and distances of throws were not recorded). Next, they walked to the bullpen mound and began warm-up throws from the mound. Each pitcher completed their normal throwing routine before pitching the simulated game. Normally, this entailed throwing 20–30 pitches. Once each pitcher felt they were properly warm, they began the simulated game, which consisted of throwing 5 warm-up pitches before each inning at submaximal velocities, throwing 14 pitches (fast balls) per inning at 95% of their best pitching velocity with 20 seconds of rest between each pitch for 5 innings, and having HR recorded after every pitch. At the end of each inning, pitchers were asked to give an RPE of their pitching effort and drank 4 oz of water. For the entire simulated game, this required each pitcher to throw 25 total warm-up pitches, 70 total game pitches, and drink 20 oz of water.

Figure 2. Arm positioning for shoulder external rotation range of motion measurement.

After throwing a complete inning, each pitcher had 6 minutes of rest, which was the equivalent of the time it took to complete the 14 pitches. During the 6 minutes of rest, the following recovery took place. Immediately after pitching, the pitcher walked to the simulated dug-out and had a blood sample drawn from a fingertip on the nonpitching hand to determine a "postpitching" blood lactate concentration. They then completed 1 of 3 recovery protocols in randomized order. Protocol 1 was a 6-minute seated PR during which the subjects simply sat in a chair in the simulated dug-out. Treatment 2 was a 6-minute AR during which the subjects pedaled an upper-body ergometer (UBE) while seated in the simulated dug-out. Treatment 3 was a 6-minute session of EMS while seated in the simulated dug-out. A blood sample was drawn from a fingertip on the nonpitching hand after the 6-minute recovery treatment session to determine a "postrecovery" blood lactate (PRLa−) concentration. Heart rate was taken every 30 seconds of the recovery during each recovery treatment to determine relative intensity values. Rating of perceived exertion was recorded after each 6-minute treatment recovery to determine relative effort of the various recovery methods.

Rating of Perceived Exertion

The modified qualitative descriptors accompanying the Borg 0–10 point RPE scale (3) were presented to the subjects alongside the numerical ratings (0.5, very, very light; 1, very light; 2, fairly light; 3, moderate; 4, somewhat hard; 5, hard; 7, very hard; 10, very, very hard). The subjects were further verbally oriented to the scale with the explanation that a score of 0.5 would represent a very, very light activity, like "easy pitching"; a score of 7 was described as a pitching intensity that would be "very challenging, but you can continue"; and a score of 10 was described as marking the "maximum effort," where he could do no more.

Passive Recovery

Passive recovery for this research project was defined as sitting in the simulated dug-out with no activity for the

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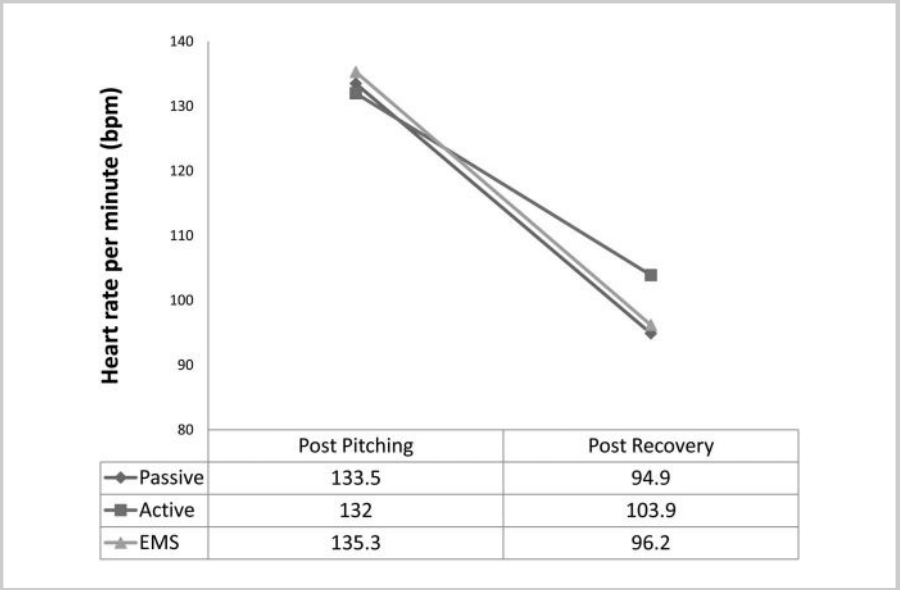

Figure 3. Mean heart rate (bpm) from post-pitching to 6-minutes post-recovery.

6-minute period. Pitchers were instructed to avoid any physical exertion during this 6-minute recovery period.

Active Recovery

The form of AR for this study was done using the Monark 881E Rehab Trainer (HealthCare International, Inc., Langley, WA, USA) UBE for the 6-minute recovery period. The pitchers were instructed to sit in the simulated dug-out while using both arms to pedal the UBE. The first 2 minutes were set at 60 W, the following 2 minutes were at 40 W, and the last 2 minutes were at 20 W. This protocol was used to mimic the decreasing intensity of the EMS recovery protocol.

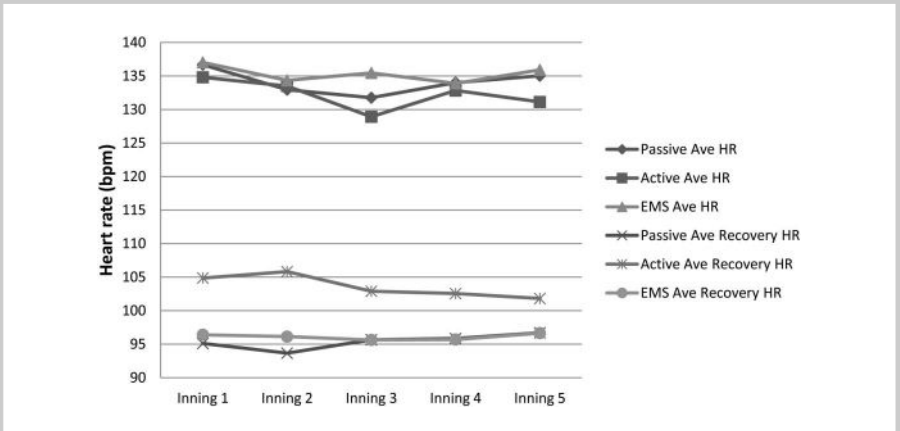

Figure 4. Average heart rate during pitching vs average recovery heart rate by inning.

Electrical Muscular Stimulation Recovery

The EMS unit that was used for this study was the Compex Sport unit (Compex Sport; Compex Technologies LLC, Ecublens, Switzerland). The participants received EMS recovery treatments using the "Active Recovery" setting, for a period of 6 minutes. The "Active Recovery" setting stimulates efferent motor neurons with a biphasic waveform. The specific setting was a rectangular biphasic symmetrical waveform, and the pulse width was 250 microseconds (0.00025 seconds). The program frequency started at 9 Hz and automatically decreased every 2 minutes. The first 2 minutes were at 9 Hz, the following 2 minutes were at 8 Hz, and the last 2 minutes were at 7 Hz. Eight electrical leads were placed on specific locations of the pitcher's throwing arm. The electricalde pads were placed on the anterior forearm flexors and posterior forearm extensors; biceps brachii and triceps brachii muscle bellies; anterior and posterior deltoid; and anterior and posterior portions of the upper trapezius (Figure 1). These muscles were selected because of their significant involvement in throwing a baseball.

Determination of Range of Motion

One tester measured all subjects' passive internal, external, flexion, and extension ROM using a standard goniometer, whereas another tester manipulated the pitcher's arm to the correct position. All measurements were taken 3 times bilaterally, and a mean of the 3 measurements was calculated and used in the investigation. Rotational measurements were taken with the subject lying in the supine position, with the shoulder abducted to 90° in the coronal plane. The elbow was flexed to 90° and the forearm was in neutral rotation.

Passive external rotation ROM was measured by moving the subject's extremity into external rotation, maintaining the positions of abduction, elbow flexion, and forearm rotation. The extremity was rotated

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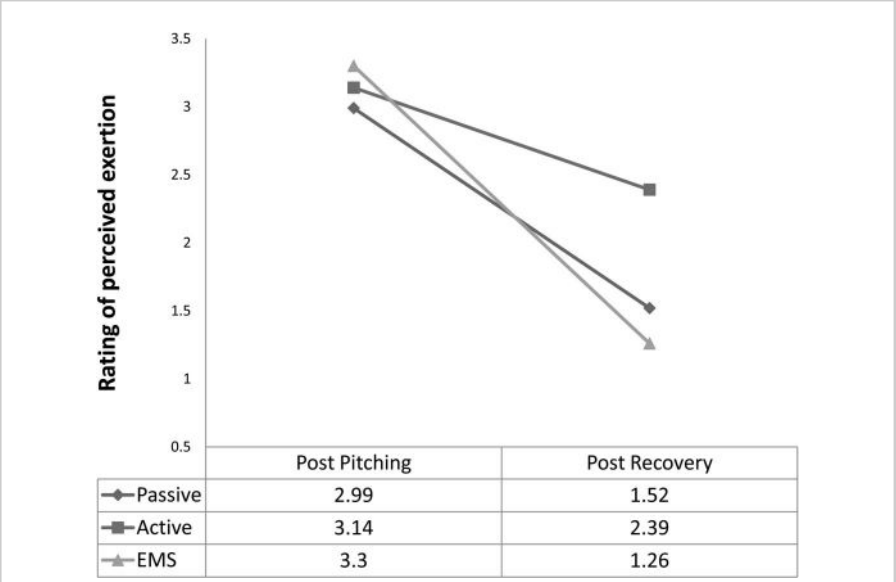

Figure 5. Mean rating of perceived exertion from post-pitching to 6-minutes post-recovery.

externally until end ROM was obtained. No passive overpressure was exerted during measurement, and the weight of the arm against gravity provided the end ROM measurement during this study. The axis of the goniometer was aligned with the olecranon process of the elbow. The stationary arm of the goniometer was aligned along the midline of the lateral forearm (Figure 2).

Passive internal rotation ROM was measured with the subject's shoulder in 90° of abduction and elbow and forearm positioning was identical to that described for external rotation. The subject's arm was internally rotated while an anterior force was applied to the coracoid and humerus to ensure that scapular compensation did not occur (10,29). No scapular protraction or upward rotation was allowed. Maximum passive internal rotation ROM was then recorded using identical goniometric landmarks.

For elbow flexion and extension measurements, the fulcrum of the goniometer was positioned over the lateral epicondyle of the humerus, with 1 arm of the device along the length of the humerus to the tip of the acromion process and the other arm along the length of the radius to the radial styloid process. Positive elbow extension was defined as motion past 0° into hyperextension. Conversely, negative elbow extension was defined as motion before 0°, such as with an elbow flexion contracture. Measurements were initially taken before any warm-up, exercise, or throwing program was performed. Measurements were then taken after pitching, and then 24 hours postpitching by the same 2 investigators.

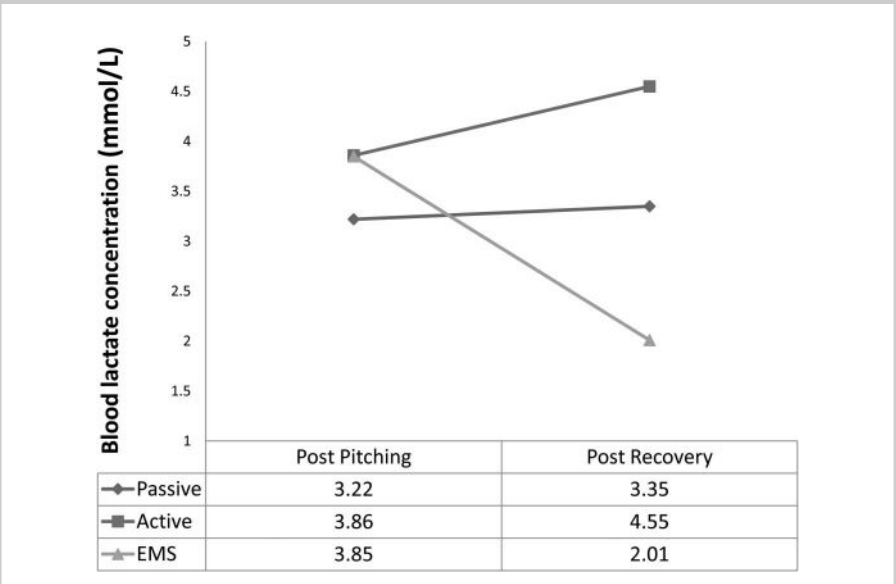

Figure 6. Mean blood lactate concentration (mmol·L^{-1}) from post-pitching to 6-minutes post-recovery.

Determination of Blood Lactate Concentration

Blood lactate concentrations were determined using a Lactate Plus blood lactate meter (Nova Biomedical, Waltham, MA, USA) that was calibrated and operated according to the manufacturer's specifications. A portable analyzer was selected so that blood lactate measurements could be made in the simulated dug-out. The analyzer works by placing a sample of whole blood on the test strip and inserting it into the analyzer for it to react with lactate oxidase. Lactate concentration is then determined from reflectance photometry in

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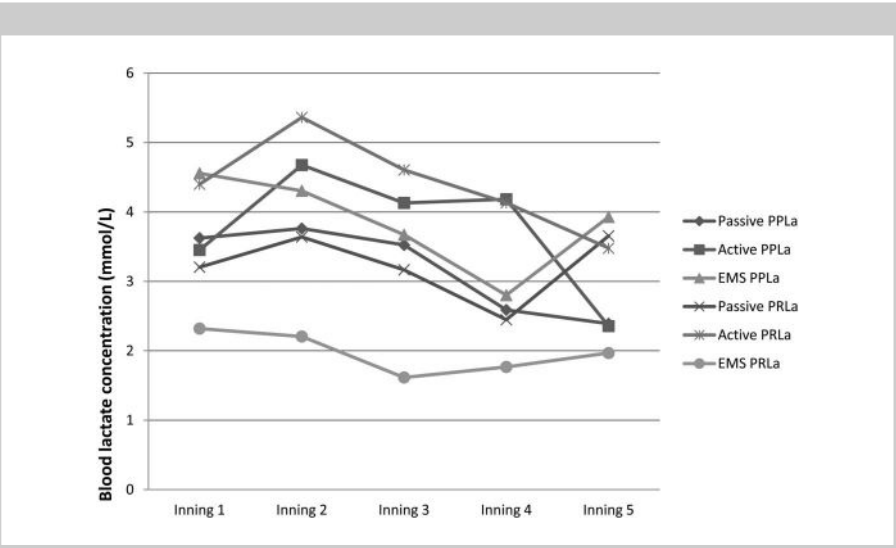

Figure 7. Average post pitching blood lactate concentration vs average post recovery blood lactate concentration by inning.

the range of 0.7–26.0 mmol·L^{-1}. The reliability and validity of the Lactate Plus analyzer have been reported in previous studies. Tanner et al. (38) showed the analyzer to be reliable (intraclass correlation coefficient [ICC] $r = 0.988$) and to demonstrate good association (ICC $r = 0.936$) with the Radiometer ABL 700 blood gas analyzer (Radiometer Medical ApS, Bronshoj, Denmark).

Blood samples were drawn from the lateral aspect of the fingertip midway between the nail plate and the inferior distal phalanx of the nonpitching hand. The sample sites were wiped with isopropyl alcohol swabs and punctured with a spring-loaded lancet device followed by 2–3 seconds of a "milking" technique (alternating pressure and release 6–8 mm from the puncture site) to enhance blood flow from the wound. Blood droplets approximately 3 mm in diameter were applied directly to the test strips for the determination of blood lactate (mmol·L^{-1}). For subsequent blood samples, if wiping the previous wound with an alcohol swab and milking the area elicited an adequate flow of blood to collect an adequate sample, no further puncture was necessary. However, if the previous site did not provide an adequate sample, a new site was selected from the nonpitching hand and used for subsequent sampling.

Recovery Preference

After all testing was competed, participants were asked to rank the recovery protocols. Rankings were assigned based on which protocol the athletes felt provided them with the best recovery being assigned as 1. The least favorable protocol for recovery was ranked as number 3.

Statistical Analyses

All statistical analyses were run using SPSS 19.0 (SPSS, Inc., Chicago, IL, USA). A 3 (recovery condition: active, passive, EMS) × 3 (time: pre, post, 24 hours postpitching) analysis of variance (ANOVA) with repeated measures on both factors was run for each of the ranges of motion. A 3 (recovery condition: active, passive, EMS) × 2 (time: pre, post) ANOVA with repeated measures on both factors was run for the following variables: HR, RPE, and blood lactate concentrations. All interactions were broken down with simple main effects testing using a Bonferroni corrected alpha. If an interaction was not observed, main effects were analyzed. An alpha level of 0.05 was chosen for all statistical comparisons. Preference for recovery method was reported using frequencies.

Results

Range of Motion

Range of motion, in any plane, did not have a different trajectory over time (pre, post, and 24 hours postpitching) for any of the 3 different recovery methods, ps > 0.05. Main effects revealed that external rotation did improve from the pre (mean = 115.3; $SE = 3.0$) to the post (mean = 118.0; $SE = 2.5$) regardless of recovery method ($p = 0.046$) but returned back to pre after 24 hours (mean = 115.7; $SE = 2.6$). Thus, the recovery methods did not differentially influence ROM in any plane although there was a small transient increase in external rotation ROM.

Heart Rate

There was a statistically significant interaction between the different recovery methods over time for HR, $F_{2,40} = 43.560$, $p < 0.001$ ($\eta_p^2 = 0.685$). Post hoc tests, using a Bonferroni corrected alpha ($\alpha = 0.01$), revealed that HR decreased during the recovery for all conditions (ps < 0.01); however, the HR for the PR method was significantly lower than the AR ($p = 0.006$). Electrical muscle stimulation recovery was not different from the PR ($p = 1.00$) or AR ($p = 0.03$) methods (Figure 3). Figure 4 shows the average HR during pitching vs. average recovery HR by inning.

Rating of Perceived Exertion

There was a statistically significant difference in the trajectory of RPE over time for the 3 different recovery methods, $F_{2,40} = 6.983$, $p = 0.01$ ($\eta_p^2 = 0.259$) (Greenhouse-Geisser corrected). Post hoc tests (Bonferroni corrected $\alpha = 0.01$) revealed a significant decline in RPE for the passive and EMS recovery methods (ps < 0.01); however, the AR

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methods did not decrease statistically over time, $p = 0.067$ (Figure 5).

Blood Lactate Concentrations

There was a different trajectory in blood lactate concentrations among the 3 recovery methods over time, $F_{2,40} = 14.058$, $p < 0.001$ ($\eta_p^2 = 0.413$). Post hoc testing with a Bonferroni corrected alpha ($\alpha = 0.01$) demonstrated that blood lactate concentrations did not change due to PR ($p = 0.684$) or AR ($p = 0.04$); however, blood lactate concentrations did decrease significantly due to EMS recovery, $p < 0.001$ (Figure 6). Figure 7 displays the average PPLa− concentration vs. average PRLa− concentration by inning.

Recovery Preference

There was a clear distinction of which recovery method was preferred the most. Of the 3 different recovery methods administered in this study, EMS was the preferred recovery method by 18 of the 21 participants. The remaining 3 participants liked PR ($n = 2$) and AR ($n = 1$) the most. Passive recovery was the second most preferred recovery method by 15 of the 21 pitchers. Active recovery was the least preferred recovery method with 16 of the 21 liking it least of the 3 recovery methods.

Discussion

Because the amount of time between innings is always unknown and ever changing in the game of baseball, finding the most effective method of recovery could have a significant impact on maintaining or enhancing a pitcher's performance and potentially reduce injuries due to fatigue. With the knowledge that as a pitcher becomes fatigued, there is an increased likelihood of injury, proper recovery should be of the utmost importance to coaches and team staff (15). Fatigue is defined as "a decrease in the maximum power of contraction" (33). The increase in blood lactate accumulation is associated with fatigue (35). Recovery is defined as the normalization of the pH within the muscle (18,19,35). This normalization can be reached with a decrease in blood lactate accumulation; this in turn should improve performance of the muscle (35). An increase in the blood flow will decrease the blood lactate accumulation to improve the performance (11,20). Within sports performance, several ideas on recovery methods have been offered. Three forms of recovery (AR, PR, and EMS) were approached within this study.

The use of EMS showed the most significant difference in blood lactate concentrations for pitchers from PPLa− to PRLa− (Figure 6). The decrease in the blood lactate concentration suggests that the muscle is receiving an effective recovery. The pitchers also felt that they received a better recovery during the EMS recovery period according to the rating of preference score. This would suggest that the muscle is being effectively flushed of blood lactate with the use of the EMS (16,17). This flushing would include an increase in the amount of new blood into the muscle. This new blood would include glycogen that would be able to be stored within the muscle more effectively due to the lack of blood lactate to prevent storage (31). Effective recovery is associated with the decrease in blood lactate. Electrical muscular stimulation provides the benefits of AR without the cardiovascular strain (31). This would allow the flushing action of the muscle without the use of the glycogen stores to do it (31). Also, there is potential to have increased neurological function, which would allow for better muscle reaction. The neurological system would be able to effectively recover by not being used and having an outside source create the muscle functions (31).

As stated earlier, AR has been shown in previous studies to be the most effective form of recovery after intensive physical exercise (5,9,12,25) and has typically been considered the "Gold" standard method for recovery (25). During this study, AR was found not to be the most beneficial form of recovery when related to blood lactate concentrations or pitcher's preference although blood flow should be increased to the upper body compared with PR due to the UBE work performed during recovery. The pitchers within this study felt that the amount of activity during the AR did not allow them to fully recover. This would correspond to the decreased rating on the recovery preference score.

Passive recovery is typically the most common form of recovery used by pitchers, as well as position players, between innings in the game of baseball. Because of this, the pitcher is accustomed to this form of recovery. However, this form of recovery does not improve recovery from a blood lactate perspective; the body simply clears what is produced. This is indicative of the PPLa− to PRLa− concentrations seen in Figures 6 and 7.

In comparison, we see that the AR had a negative effect on the pitcher's blood lactate concentrations (Figures 6 and 7). Since the amount of time between innings of a baseball game is never the same and not predetermined, the data from this study indicate that AR should not be used as an effective recovery method for baseball pitchers. There is not enough time to properly use and receive the effects of an AR. The blood lactate concentrations and RPE are higher in relation to PR and EMS recovery methods used in this study.

The EMS recovery and PR were the 2 recovery methods most preferred by pitchers in this study. Electrical muscular stimulation had the most significant effect on blood lactate concentrations from PPLa− to PRLa−, suggesting that pitching fatigue may be delayed. If this occurs, then the potential to decrease injuries may occur. Passive recovery would be an effective form of recovery for a pitcher if EMS was unavailable. However, since PR allowed HR to decrease significantly more than AR or EMS, blood lactate was not cleared as effectively as EMS. But, PR spares muscle glycogen utilization compared with AR since muscles are not activated during recovery. The body can physiologically adapt to become more effective in the filtration of the blood during this recovery time, partially because there would not be a work load slowing biological processes down.

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Electrical muscular stimulation was significantly more beneficial to the pitchers. The pitchers were able to receive the benefits of the PR, decreased HR and biological activity, as well as the sparing of muscle glycogen since muscles were not activated compared with AR. Since the electricity used to cause the contractions of the muscle is from the stimulation unit, no glycogen is needed to cause the muscle contraction. The EMS not only bypasses the neurological system to force the contraction but also receives the benefits of AR, which is the activity of the muscles to flush the blood and receive clean blood back into the muscles. (16,17,31,32) Pitching velocity was maintained throughout the 5-inning simulated games because of the 20 seconds of rest between pitches, low RPE postpitching and postrecovery, and 6 minutes of rest between innings. Further research is needed to validate this concept. It is known that fatigue causes poor mechanics and will lead to an increase in injury (7,15,32,44,46). Further studies need to be performed to find if effective recovery will decrease the injury rate. However, pitchers will need to throw more than 14 pitches per inning as this is the average number of pitches thrown per inning in college baseball.

Practical Applications

Although EMS significantly reduced blood lactate concentrations after recovery, blood lactate concentrations after pitching in the simulated games were never high enough to cause skeletal muscle fatigue and decrease pitching velocity. If a pitcher were to throw more than 14 pitches per inning, throw more total pitches than normal per game, and have blood lactate concentrations increase higher than in the simulated games in this study, the EMS recovery protocol may be beneficial to pitching performance by aiding recovery. This could potentially reduce some injuries associated with skeletal muscle fatigue during pitching, may allow a pitcher throw more pitches per game, and may reduce the number of days between pitching appearances.

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Effects of Whole-Body Electromyostimulation on Resting Metabolic Rate, Body Composition, and Maximum Strength in Postmenopausal Women: the Training and ElectroStimulation Trial

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[1]Institute of Medical Physics, Friedrich-Alexander University, Erlangen-Nürnberg, Germany; [2]Institute of Sport Sciences, Friedrich-Alexander University, Erlangen-Nürnberg, Germany; and [3]Department of Exercise Science, Truman State University, Kirksville, Missouri

Abstract

Kemmler, W, Schliffka, R, Mayhew, JL, and von Stengel, S. Effects of whole-body electromyostimulation on resting metabolic rate, body composition, and maximum strength in postmenopausal women: the Training and ElectroStimulation Trial. *J Strength Cond Res* 24(7): 1880–1887, 2010–We evaluated the effect of whole-body electromyostimulation (WB-EMS) during dynamic exercises over 14 weeks on anthropometric, physiological, and muscular parameters in postmenopausal women. Thirty women (64.5 ± 5.5 years) with experience in physical training (>3 years) were randomly assigned either to a control group (CON, $n = 15$) that maintained their general training program (2×60 min·wk^{-1} of endurance and dynamic strength exercise) or to an electromyostimulation group (WB-EMS, $n = 15$) that additionally performed a 20-minute WB-EMS training (2×20 min·10 d^{-1}). Resting metabolic rate (RMR) determined from spirometry was selected to indicate muscle mass. In addition, body circumferences, subcutaneous skinfolds, strength, power, and dropout and adherence values. Resting metabolic rate was maintained in WB-EMS (-0.1 ± 4.8 kcal·h^{-1}) and decreased in CON (-3.2 ± 5.2 kcal·h^{-1}, $p = 0.038$); although group differences were not significant ($p = 0.095$), there was a moderately strong effect size (ES = 0.62). Sum of skinfolds (28.6%) and waist circumference (22.3%) significantly decreased in WB-EMS whereas both parameters (1.4 and 0.1%, respectively) increased in CON ($p = 0.001$, ES = 1.37 and 1.64, respectively), whereas both parameters increased in CON (1.4 and 0.1%, respectively). Isometric strength changes of the trunk extensors and leg extensors differed significantly ($p \leq 0.006$) between WB-EMS and CON (9.9% vs. −6.4%, ES = 1.53; 9.6% vs. −4.5%, ES = 1.43, respectively). In summary, adjunct WB-EMS training significantly exceeds the effect of isolated endurance and resistance type exercise on fitness and fatness parameters. Further, we conclude that for elderly subjects unable or unwilling to perform dynamic strength exercises, electromyostimulation may be a smooth alternative to maintain lean body mass, strength, and power.

Key Words body composition, exercise, RMR, muscle, aging

Introduction

The change of body composition and the corresponding decline of functional capacity from maturity to senescence, even in healthy subjects, are of clinical significance. In the USA each year, about 10% of the nondisabled adults 75 years and older lose independence to perform the basic activities of daily living because of disability (16). After the menopausal transition, body composition changes considerably in elderly women. These changes include a clinically relevant increase of body fat together with a reduction of muscle mass (15,35); both factors correlate with morbidity and mortality in this age cohort (9). Parallel to these body composition changes, strength decreases by 15% per decade after the age of 60 years (12). However, although exercise studies (1,10,32) have observed favorable changes of body composition and strength parameters, because of physical limitations or a simple aversion, a large number of elderly subjects seem to be either unable or unwilling to perform (intense) exercise programs (19,25).

In this context, whole-body electromyostimulation (WB-EMS) may be a smooth alternative to demanding conventional exercise programs (40). Although the favorable effect of *local* electromyostimulation on (neuro) muscular parameters has been previously determined in athletes (4,5,13,26),

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healthy younger (13,17,18), and elderly subjects (2,27,28,38), the overall effect of WB-EMS on body composition and strength in elderly subjects is scarce. Also important, the feasibility and acceptance of this exercise technology is unknown in this cohort.

Thus, in this pilot study, we determine the effect of WB-EMS on body composition, strength parameters, feasibility, and acceptance in a group of postmenopausal women. Our hypothesis was that WB-EMS exercise favorably affects body composition and strength in this cohort.

Methods

Experimental Approach to the Problem

We performed a 14-week randomized controlled trial with postmenopausal women to address our hypothesis. To ensure that participants adequately perform the WB-EMS exercise regime, we included only women with a long experience of resistance training. Further, both subgroups performed the same basic exercise training described below; however, only the verum group performed an additional WB-EMS regime over 14 weeks (March 2008 to July 2008).

Endpoints representing our primary targets "body composition" and "maximum strength" were skeletal muscle mass indirectly assessed by spirometry (resting metabolic rate [RMR]), body fat assessed by skinfold measurement and bioimpedance analysis (BIA), abdominal fat determined by waist circumference, and isometric trunk, and leg strength.

The study design allows us to determine the additional effect of WB-EMS training on the above-mentioned endpoints in comparison to an isolated endurance and strength training program.

Subjects

Thirty postmenopausal women 55 years and older, living in the community of Erlangen-Nurnberg and pretrained during the Erlangen Fitness and Osteoporosis Study (EFOPS) (21) or Senior Fitness and Prevention Study (SEFIP) exercise studies (24) for >3 years were included in the Training and ElectroStimulation Trial (TEST). Both studies were trialsthat focused on general fitness with special regard to bone parameters with a combined high intensity endurance, resistance, and balance regime with 2 joint sessions and 2 home-training sessions per week.

Exclusion criteria (according to the manufacturer) were epilepsy, cardiac pacemaker, grave circulatory disorders, abdomen or groin hernia tuberculosis, cancer, grave neurologic disturbances, inflammable diseases, bleeding tendencies, medication, or diseases affecting muscle metabolism.

The study was approved by the ethics committee of the University of Erlangen (Ethik Antrag 3777). All study participants were informed of the experimental risk and gave written informed consent.

Figure 1 shows the participant flow during the TEST study. Subjects were stratified by age and randomly assigned to 2 intervention groups: WB-EMS ($n = 15$) or control (CG: $n = 15$). In addition to the endurance and strength training described below, the WB-EMS group performed WB-EMS training every 4–5 days (see below), whereas the CG were asked to maintain their previous exercise training. Table 1 gives the initial characteristics of the WB-EMS and control group.

Procedures

Intervention. Basic Exercise Program. The basic exercise program has been described elsewhere in detail (21–23); thus, only a brief description is given here. The exercise program consisted of 2 supervised group sessions (60–65 minutes) and 2 home-training sessions (20–25 minutes) per week. During these sessions, 20 minutes of aerobic dance (70–85% HRmax) were followed by multilateral jumps (4 × 15 reps) and either by 40 minutes of functional gymnastics and barbell exercises (3 exercises, 2 sets, 6–12 reps at 70–85% 1 repetition maximum [1RM]) or dynamic resistance training with strength machines (12 exercises, 1–3 sets, 6–12 reps at 70–85% 1RM).

Electromyostimulation. In addition to this basic exercise training, the WB-EMS group performed a guided and supervised WB-EMS training (miha bodytec, Augsburg,

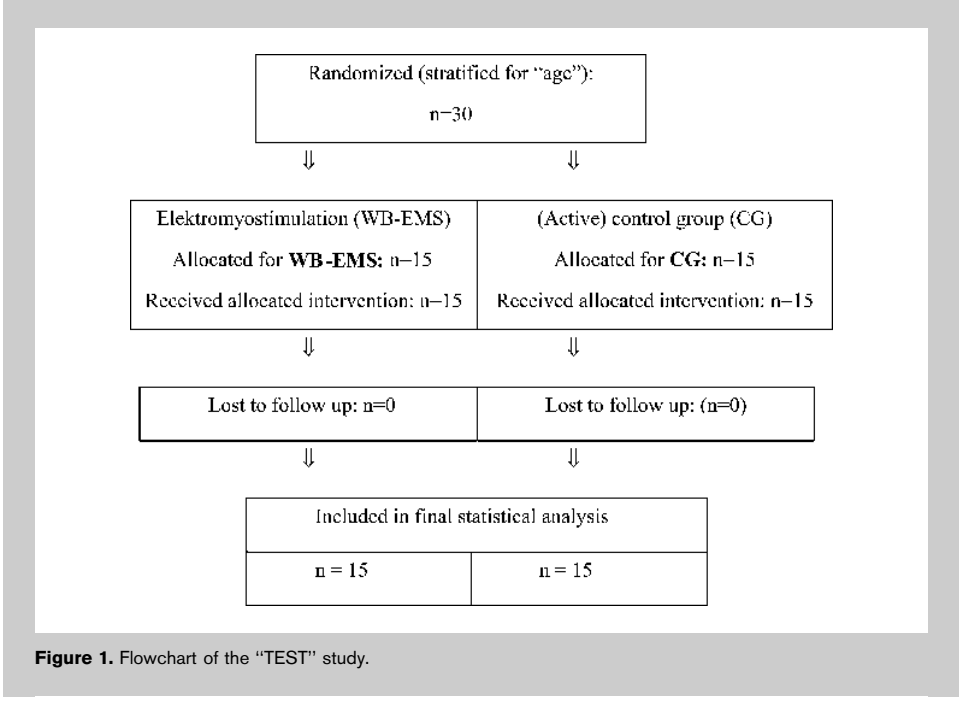

Figure 1. Flowchart of the "TEST" study.

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Germany, Figure 2) every 4–5 days. The WB-EMS equipment enables the simultaneous activation of 10 regions (upper legs, upper arms, bottom, abdomen, chest, lower back, upper back including the latissimus dorsi) with different intensities (Figure 2). Participants carried out 2 standardized WB-EMS programs during a 20-minute session (Table 2).

Fifteen dynamic exercises for all large muscle groups using a small range of movement were performed during WB-EMS training. Exercises were designed not to cause physical adaptations in this pretrained cohort. Current intensity of the WB-EMS was progressively increased during the interventional period.

Compliance with the WB-EMS regime was determined after 6 and 14 weeks. Participants were asked to appraise the average intensity of a WB-EMS session and the regional intensity of the WB-EMS on a rating scale (Ratings of Perceived Exertion [RPE]) between 1 (very low) and 7 (very high). Attendance was recorded by training logs managed by research assistants.

Testing Procedures

Tests were carried out before and after 14 weeks of exercise by the same researcher and at the same time of the day (±1 hour). All assessments were determined in a blinded fashion.

Height was determined with a stadiometer, and weight was measured with minimal clothing on digital scales. Body mass index was calculated as weight divided by height squared ($kg \cdot m^{-2}$). Circumferences were determined at several locations including the waist and hip. Body fat was assessed by skinfold measurement (Lange, Cambridge, MA, USA) at 11 anatomical sites (tragus, mouth, axilla, subscapularis, abdominal, supraillacus, suprapatella, biceps brachii, triceps brachii, and gastrocnemius). Tests were performed twice; the mean value of both tests were included in the analysis. The coefficient of variation was <5.3% for this procedure (multiple-tester reliability).

Resting metabolic rate was determined between 7:00 and 9:00 at a constant room temperature of 23° C before and after the 14-week intervention using indirect calorimetry after 12 or more hours of fasting. Participants were instructed not to participate in heavy physical activity or exercise 24 hours before the test and to visit the laboratory by car or public transport. Participants rested in a supine position quietly for 15 minutes before the data collection and for an additional 15 minutes during which the data were sampled. Subjects breathed freely through a face mask with expired air analyzed

Table 1. Baseline characteristics of the TEST cohort: EMS vs. CG.*†

Variable	WB-EMS ($n = 15$)	CG ($n = 15$)	p
Age (y)	65.6 ± 5.6	63.3 ± 5.4	n.s.
Height (cm)	160.8 ± 5.4	162.2 ± 6.6	n.s.
Weight (kg)	70.4 ± 12.0	64.9 ± 10.9	n.s.
Total body fat (%)‡	37.9 ± 4.8	35.0 ± 2.7	§
Age at menopause (y)‖	48.9 ± 5.2	47.9 ± 4.1	n.s.
Energy intake ($kJ \cdot d^{-1}$)¶	7,689 ± 1,722	7,824 ± 1,640	n.s.
Protein intake ($g \cdot d^{-1}$)¶	65 ± 17	71 ± 21	n.s.
Exercise volume ($min \cdot wk^{-1}$)‖	179 ± 58	147 ± 43	n.s.
VO_2peak ($ml \cdot kg^{-1} \cdot min^{-1}$)#	27.1 ± 4.1	26.9 ± 4.2	n.s.
Multimorbidity (% per group)**	53.3	46.7	n.s.

*EMS = electromyostimulation; CG = control group; WB-EMS = whole-body-electromyostimulation; n.s. = nonsignificant.
†Values are given as mean ± *SD*.
‡Skinfolds according to Durnin and Wormserley (11).
§$p < 0.05$.
‖Baseline questionnaire.
¶Four-day dietary protocol.
#Spirometry; treadmill test to a voluntary maximum.
**Two and more diseases.

Figure 2. Whole-body electromyostimulation equipment.

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using an open spirometric system (Oxycon mobile, Conshohocken, PA, USA). Coefficient of variation determined in a recent pilot study was 4.1% for this procedure.

Maximum isometric strength of the trunk and leg extensors was measured with a Schnell M3 isometric tester using the test protocol suggested by Tusker (36). The coefficients of variation were <4.0% (3.1% for trunk extension to 3.9% for leg extension) for this procedure.

A detailed questionnaire was used to assess well-being, pain frequency, and intensity at different skeletal sites, prestudy exercise levels, normal daily activity levels, diseases, and medication. The follow-up questionnaires additionally contained sections to monitor disease incidences, changes in disease severity and intake of medication, life-style changes, or sport activities outside the TEST training program.

Statistical Analyses

The sample size calculation was based on our main endpoint RMR. To detect a 5% difference between the groups, 15 subjects per group were required for a 5% error probability with 80% statistical power (*SD*: 5%; Dropout rate: $n = 2$). Baseline values were reported as means and *SD*s. Normal distribution was checked using the Kolgomorov–Smirnov test, and homogeneity of variance was investigated with Levine's *F*-test. Normally distributed variable differences within groups were analyzed by paired *t*-tests, otherwise the Wilcoxon–rank test was used. Changes between baseline and 18 months follow-up were reported as absolute changes. Depending on the data, Mann–Whitney *U* test based on absolute changes or analyses of variance with repeated measurements were performed to check time–group interactions. Between-group differences were given as absolute difference along with 95% confidence interval (Table 3). All tests were 2-tailed, and statistical significance was accepted at $p \leq 0.05$. Effect sizes (ES) based on the absolute difference ($\pm SD$) between baseline and follow-up in the WB-EMS vs. the CG were calculated using Cohens' *d* (8). SPSS 16.0 (SPSS Inc, Chicago, IL, USA) was used for all statistical procedures.

Results

Overall attendance rate of the basic exercise program did not change compared with prestudy attendance and was comparable between both groups (≈80%; 22.3 ± 2.0 total sessions). Attendance rate of the WB-EMS training was 98%. No incidents of medical significance occurred during the training sessions.

Average exercise intensity per session was characterized as moderate to high (RPE: 4.4 ± 0.5) after 6 weeks and increased (4.9 ± 0.7) after 14 weeks of WB-EMS exercise. After 6 weeks, with 1 exception (chest: 3.4), regional EMS intensity was described as moderate for all other regions (3.9 ± 0.3, 3.7–4.1). The perceived exposure significantly increased after 14 weeks of WB-EMS training (4.7 ± 0.5; 4.2–5.4).

The effect of the WB-EMS program on primary and secondary study endpoints is given in Table 3. In summary, RMR significantly decreased in the CG (−5.3%, $p = 0.038$) and did not show relevant changes in the electromyostimulation group (−0.2%, $p = 0.991$). Despite a moderate ES (ES = 0.62), no significant differences ($p = 0.095$) between the groups were determined.

Body weight significantly decreased in both groups (WB-EMS: 1.9 ± 1.7 kg, $p = 0.001$ vs. CG: 0.9 ± 1.5 kg, $p = 0.025$); however, changes in body weight over the training was not significantly different between WB-EMS and CG ($p = 0.122$, ES = 0.62) after 14 weeks.

Sums of skinfolds were significantly reduced in the WB-EMS ($p = 0.001$) by 8.6%. A nonsignificant increase of this parameter was observed in the CG (1.4%), whereas difference between groups was significant ($p = 0.001$; ES = 1.37). Corresponding data were obtained for BIA measurement ($p = 0.001$; ES = 1.22).

Waist and hip circumferences were also significantly ($p = 0.001$) reduced in the WB-EMS, both by ≈2.3%. In the CG, waist circumference increased nonsignificantly ($p = 0.106$) by 1.0%, whereas hip circumference significantly ($p = 0.008$) decreased by 1.3%. Significant between-group differences were determined for waist circumference ($p = 0.001$, ES = 1.64).

Maximum isometric strength of the trunk and leg extensors of the WB-EMS group significantly improved by 9.9% ($p = 0.015$) and 9.6% ($p = 0.001$), respectively. Both parameters decreased nonsignificantly in the CG (trunk extensors: −6.4%, $p = 0.054$; leg extensors: −4.5; $p = 0.106$). Whole-body electromyostimulation and CG significantly ($p < 0.01$) differed on these parameters after 14 weeks (ES = 1.53 and 1.43, respectively).

Because we observed a low incidence of pain intensity and frequency at baseline, the lack of significant differences among WB-EMS and CG for these parameters were not unexpected after 14 weeks of intervention.

Table 2. Whole-body electromyostimulation-protocol of the TEST study.

Program 1	Program 2
Stimulation frequency: 85 Hz	Frequency: 7 Hz
Impulse duration: 4 s	Impulse duration: continuously
Impulse break: 4 s	
Impulse increase: 0 s	
Pulse breadth: 350 μs	Pulse breadth: 350 μs
Impulse type: bipolar	Impulse type: bipolar
Duration: 10 min	Duration: 10 min

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Table 3. Changes of primary and secondary endpoints in the WB-EMS and control group.*†‡

	EMS ($n = 15$) (MV ± *SD*)	CG ($n = 15$) (MV ± *SD*)	Absolute difference mean (95% CI)	*p*	Effect size
RMR (kcal·h^{-1})					
Baseline	61.6 ± 10.6	60.0 ± 9.7			
14 wk	61.6 ± 9.5	56.8 ± 9.2			
Difference	−0.1 ± 4.8	−3.2 ± 5.2	−3.2 (−7.0 to 0.6)	0.095	0.62
Sum of 11 skinfold (mm)					
Baseline	267.8 ± 68.8	227.4 ± 30.3			
14 wk	244.6 ± 54.6	230.2 ± 32.1			
Difference	−23.2 ± 20.1	2.8 ± 17.7	26.1 (11.9–40.2)	0.001	−1.37
Waist circumference (cm)					
Baseline	86.5 ± 10.9	80.8 ± 7.1			
14 wk	84.4 ± 54.6	81.6 ± 6.6			
Difference	−2.0 ± 1.5	0.8 ± 1.9	2.8 (1.6–4.1)	0.001	−1.64
Hip circumference (cm)					
Baseline	106.3 ± 10.2	101.0 ± 6.6			
14 wk	103.6 ± 9.5	99.7 ± 6.2			
Difference	−2.5 ± 1.8	−1.3 ± 1.6	1.2 (−0.1 to 2.5)	0.065	−0.70
Isometric maximum strength trunk–extensors (N)					
Baseline	116.3 ± 23.8	119.5 ± 40.0			
14 wk	127.8 ± 44.2	112.0 ± 32.2			
Difference	11.5 ± 12.8	−7.6 ± 12.2	−19.2 (−32.4 to −6.0)	0.006	1.53
Isometric maximum strength leg extensors (N)					
Baseline	827 ± 209	889 ± 191			
14 wk	908 ± 229	849 ± 214			
Difference	80 ± 77	−40 ± 90	−121 (−184 to −57)	0.001	1.43

*WB-EMS = whole-body electromyostimulation; RMR = resting metabolic rate.
†Significance (*p*) is listed for between-group differences only; further information is given in the corresponding Result section.
‡n.s. = nonsignificant.

Discussion

To the best of our knowledge, the present study is the first clinical trial that determined the feasibility and, with 1 limitation the effectiveness of WB-EMS on body composition and strength in a postmenopausal cohort. Thus, we could verify our hypothesis up to the point that WB-EMS has a significantly positive impact on overall and abdominal fat and on strength parameters. However, lean body mass (LBM) indirectly determined via RMR showed a nonsignificant effect ($p = 0.095$; ES: 0.62) after adjuvant WB-EMS.

Compared with other studies with comparable duration (3), dropout rate was low, and attendance was excellent in the WB-EMS group. However, one has to realize that our WB-EMS program was related to rather individualized training sessions with 1 instructor and 2 participants. Thus, it may be rather the exclusiveness of the exercise program than its mode that leads to this exceptional high commitment.

Judging the overall effectiveness of WB-EMS in this cohort of pretrained and physically adapted subjects is difficult. The focus of this study was to determine the effect of an adjuvant WB-EMS program on a variety of body composition and strength parameters in a pilot study design. This may have limited us in several ways. First, we recruited a cohort of pretrained women that were capable of realizing the prescribed perceived exertion rate for the WB-EMS program. This proceeding may be suboptimum concerning the development of our endpoints; however, comparable to conventional exercise protocols, it was essential that exercise intensity (i.e., current intensity) was high enough to overwhelm individuals' strain threshold. Secondly, exercise and control groups maintained their conventional exercise training to not disrupt the training continuity, especially of the control group. Although both groups performed the same basic exercise protocol with identical attendance, there may be a synergistic effect that favored the results of the WB-EMS group. Thirdly, we did not perform high-end body composition measurements (i.e., computed tomography [CT] or dual energy X-ray absorptiometry [DXA]) to minimize the bureaucratic expenditure. Hence, greater changes in body composition might have occurred than were able to be determined by the precision of our measurements.

Despite the aforementioned limitations, after 14 weeks of intervention, we determined positive WB-EMS effects on all anthropometrical and muscular endpoints. Although we did

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not establish a sedentary control group for reasons discussed above, differences between groups reached statistical significance for fitness (strength parameters) and total and abdominal fatness (sums of skinfolds and waist circumference) parameters.

Concerning our primary endpoint, however, the WB-EMS effect on RMR did not reach statistical significance. Resting metabolic rate was selected as our primary endpoint for 2 reasons. Primarily, from a methodological point of view, RMR represents a key determinant of the magnitude of fat-free mass (FFM) (33). Thus, changes of RMR may indicate changes of FFM. Although FFM is a heterogenic compartment (muscle, organs, bone, and connective tissue), exercise-induced changes of FFM can be almost exclusively dedicated to changes of muscle mass.

Further, with 60–70% of the subjects, RMR is the largest component of daily energy expenditure (34), meaning that exercise strategies to decrease or maintain body weight or body fat should focus on FFM. Thus, although compared with DXA, Magnetic resonance imaging, or quantitative computed tomography (QCT), RMR may be a suboptimum parameter to determine muscle mass per se; RMR assessment additionally gives an insight into basic energy consumption of these postmenopausal women.

A central cause for the failure of the study to determine a significant effect on RMR may have been a less than adequate statistical power, resulting in a higher deviation of the mean difference than expected (8% vs. 5%). Several reasons may contribute to this higher variance. (a) A low reliability of the RMR assessment may have been present. This factor, however, can be neglected because the CV of our RMR measurement was comparable with corresponding studies (37). (b) Changes of confounding factors with impact on RMR during the intervention period were determined by interview or questionnaire; however, no subject reported major corresponding changes. (c) Also, all subjects followed the prescribed protocol, which meant no subject participated in heavy physical activity or exercise 24 hours before the test or visited the laboratory by other means than car or public transport such as bicycling or walking.

Thus, the most likely reason for the high intraindividual variation of the adaptability to WB-EMS (−5.3 to 8.4%) may be either the exercise compliance in the WB-EMS group or a high variation of the corresponding effect of WB-EMS on RMR in pretrained postmenopausal women (31). Concerning the first issue, although attendance was rather high in the WB-EMS group, it was difficult to decide whether subjects realized the prescribed exercise intensity during the WB-EMS training.

Regarding the development of RMR, it is interesting that the WB-EMS group maintained their rates, whereas RMR of the CG significantly dropped. Although a systematic error concerning the spirometric assessment may be a reason, the quality control parameters of this procedure did not support this idea. A more evident reason for the change of RMR may be individuals acclimatization induced by seasonal variations during the test and intervention phase from March to July (7).

Both groups reduced their body weight significantly, with only one subject per group listing an energy restricting diet as a reason. Comparable to the RMR, the reduction of body weight may be related to seasonal changes of nutritional habits and energy intake (39). Whether energy restriction was generally related to changes of RMR and body weight is difficult to conclude. In their review, Stiegler and Cunliffe (34) summarized the effect of energy restriction and combined exercise training (endurance and strength type, comparable to our basic exercise program). Dependent on protein intake, the authors determined that there was at least maintenance of the FFM. After progressive, high-intensity resistance training combined with an energy-restricted diet (800 $kcal \cdot d^{-1}$ with 40% proteins) in a cohort of overweighted subjects, Bryner et al. (6) determined a significant reduction of body weight (15%) combined with a marginal decrease of the FFM (−1.6%) and a significant increment of the RMR (3.6%). In parallel, the low-moderate reduction of body weight in our nonsedentary CG should not result in a significant decrease of the RMR.

Besides the significant reduction of body weight in the WB-EMS group, a significant decrease of subcutaneous body fat as assessed at 11 skinfold sites along with a significant reduction of the abdominal body fat as determined by waist circumference assessment (20,30) was shown in the presence of maintenance of RMR.

Reviewing the literature, there is a lack of studies determining the effect of whole-body myostimulation on body composition in the elderly. Although some studies demonstrated an increase in muscle mass after myostimulation (27,38), no study has yet assessed the effect on total or central body fat.

Concerning maximum strength changes, our WB-EMS group that performed an endurance and strength type basic program together with a WB-EMS program exhibited significant differences compared with a CG that performed an isolated strength and endurance exercise program. Most studies with untrained subjects confirmed our results (13,28,38). In one study, the isolated effect of local EMS on isokinetic quadriceps strength was compared with an isolated EMS program and a combined stair climbing and EMS program (28). Contrarily to our results, Paillard et al. (28) did not obtain significant differences concerning the strength changes between the groups. However, unlike our cohort, their exercise subjects were college "freshmen" producing a consider age differential.

One may argue that the difference between the isolated basic exercise group (CG) and the combined exercise and WB-EMS group did result from a higher training volume of the WB-EMS group. However, this argument may be confounded by dose-effect phenomenon in studies of strength type exercise (14,29).

In summary, in this group of pretrained elderly subjects, a high acceptance and feasibility of whole-body EMS training exercise was verified. Further, we provided evidence that

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adjuvant WB-EMS exercise exceeds the effect of isolated strength and endurance type exercise for fitness and fatness parameters.

Practical Applications

It is obvious that an increasing number of elderly subjects are unable or unwilling to perform (intense) conventional exercise training regimes. The findings of the study demonstrate that whole-body EMS program performed for 20 minutes every 4 days is effective and feasible. Thus, we consider the application of this novel exercise technology an appropriate alternative for elderly subjects to favorably improve body composition and physical strength important for healthy and independent aging. As a result, WB-EMS as a means of exercise training that focuses on body composition and strength parameters should be taken seriously into account by end users, physical therapists, and physical fitness instructors.

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Effect of Three Different Between-Inning Recovery Methods on Baseball Pitching Performance

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Abstract

Warren, CD, Brown, LE, Landers, MR, and Stahura, KA. Effect of three different between-inning recovery methods on baseball pitching performance. *J Strength Cond Res* 25(3): 683–688, 2011—A decrease in blood hydrogen ions (H^+) may allow for the recovery of a muscle, which should allow for greater performance in subsequent activity. The purpose of this study was to determine which of 3 forms of recovery were the most effective after an inning of pitching in baseball. Three different measurements were used to determine which recovery method was most effective; the difference in blood lactate (BLa) levels was used as a biological measurement, average pitching speed was the physiological measurement, and the psychological measurement was done on how the pitchers perceived their pitching and recovery. The recovery methods that were used were passive recovery (PR), active recovery (AR), and electromuscular stimulation (EMS). Seven college men aged 21 (±2 years) who were National Collegiate Athletic Association Division II college baseball pitchers were assessed during game play simulations. Blood lactate levels decreased significantly from the premeasurement to the postmeasurement with the EMS recovery method ($p < 0.0005$); however, BLa did not change for PR ($p = 0.017$) or AR ($p = 0.134$). Perceived recovery was also found to be best in the EMS and PR conditions. These findings suggest that EMS is an effective recovery method between innings of pitching.

Key Words electrostimulation, passive, blood lactic acid

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Introduction

There have been continued efforts to find more effective training techniques and to investigate the science of muscular adaptations and recovery (6). With advances in both technology and an understanding of training methods, insights into the balance between performance and recovery time have become better understood. Because performance on the field in competitive situations is what is most scrutinized by all stakeholders, this isolated period of time receives the most attention. For baseball pitchers, this means being able to perform at optimal levels consistently. An example of the implications of a rest period being important is the advent of management sticking more than ever before to a 100-pitch count. Ironically, despite the introduction of the 100-pitch count and the increased use of relief pitchers, the injury rate of pitchers continues to increase (10). If the decrease in the number of pitches is not improving pitching, then can recovery between innings improve pitching?

As pitchers continue to do repetitive high-intensity motions, blood lactic acid (BLa) levels will increase in the involved muscles and general circulation. The accumulation of BLa increases hydrogen ions (H^+) and causes a decrease in the pH within the muscle; low pH mediated by increased BLa levels can impair motor control during pitching (3,11,15). This is because of several factors including the following: decreased blood flow and low oxygen content in the blood, and lack of aerobic recovery to flush the waste product H^+ from the shoulder (1,15). This can impair motor control during the pitching process (3). Finding the most effective form of recovery is beneficial when trying to maintain or enhance a pitchers performance (18). As a pitcher becomes fatigued, there is an increased likelihood of injury; therefore, recovery is of utmost importance (5). In addition, fatigue may cause a decrease in the maximum power of muscular contraction (13). From a recovery perspective, an increase in blood flow may decrease H^+, which would in turn potentially mitigate fatigue and the likelihood of subsequent injury. Moreover, an increase in blood flow may lead to improved performance (3,8).

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Several strategies to facilitate recovery have been investigated in the literature, including active recovery (AR), passive recovery (PR), and electromuscular stimulation (EMS). The AR, wherein athletes participate in an active movement, often cardiovascular, in an effort to increase blood flow, has been shown in previous studies to be the most effective form of recovery (1,3). The rationale for AR is to allow vasodilatation and oxygen rich blood to increase the rate of H^+ clearance in the muscle. It has been found that the best AR has come from activity at about 60% of estimated maximum heart rate and slowly declining the estimated maximum heart rate to about 30% (7,9,17).

Passive recovery is simply rest, often in the form of sitting, lying down, or stretching. Typically, 15–25 minutes of rest is thought to be the optimal time for returning pH levels to normal (1). This form of recovery has the ability to allow the body to maintain and rebuild its glycogen stores, because of its inactive method (2). Passive recover in some studies has shown to have the same effect of lowering BLa as AR but without the energy expenditure (3,12).

Electromuscular stimulation, which is a relatively new modality for postexertional recovery, has received very little attention in the literature. It is based on the principle that EMS induces local muscle contraction without corticospinal excitation, thereby increasing blood flow and reducing lactic acid build-up. Studies have shown that EMS increases blood flow more than when voluntary muscle exercises are used (8,19,20). This increase of blood flow has been shown to help reduce H^+ levels associated with lactic acid build-up (19). The theoretical advantage of EMS is that focal muscle stimulation can increase blood flow without accelerating the heart frequency and without increasing arterial blood pressure (13). Thus, muscle contractions occur without cardiovascular strain or mental fatigue (4).

Presently, there is little evidence to support the use of 1 recovery method over another between innings while pitching in a baseball game. Therefore, the purpose of this study was to determine which of the 3 aforementioned recovery methods (AR, PR, and EMS) would be the most appropriate to administer during the rest periods between innings in baseball pitchers. Two primary aims and 1 secondary aim guided this study. Our primary aim was to determine which of the 3 recovery methods was best at decreasing BLa levels in the rest period between innings. A second primary aim was to determine if the BLa levels for each of the 3 recovery methods was consistent with how the pitchers perceived their recovery for each of the 3 recovery methods. A secondary aim was to determine if the intensities of the inning before administration of the recovery methods were consistent across the 3 conditions. This would be done by measuring the average pitch speed and self-reported pitching intensity.

Methods

Experimental Approach to the Problem

All participating pitchers received instruction and demonstrations on the testing procedures before the start of the study. The design of the pitching order and format was based on the typical pitching format used by most baseball teams. Pitchers were to follow the normal pitching recovery routine, as prescribed by the pitching coach, between testing days. The pitchers were placed on a 4-day pitching rotation and performed the protocol exercises, as directed by the pitching coach, on nonpitching days. Pitchers were instructed to follow the dietary and hydration protocols as instructed by their pitching coach. For the conditions to most closely approximate an actual game, pitchers were evaluated during live game play practices. Pitchers were tested at roughly the same time every testing day. There was no control of a pitcher's pitching order, the number of pitches, or the amount of time for recovery between innings. This allowed for the most accurate simulation of game play, and was done to try to prevent the pitchers from changing their normal pitching routine. Pitching was done outdoors and in the cool to cold weather typically found with preseason conditions. On assigned live pitching days, players were to follow normal warm-up procedures. Immediately after pitching, BLa was tested. The pitchers also rated their pitching performance at this time. The selected recovery method was done for 6 minutes. At the end of 6 minutes, BLa was retested, and they rated their recovery. This was repeated for 3 innings using the same form of recovery for each inning. Each pitcher was exposed to all 3 forms of recovery.

Subjects

Seven college men with a mean age of 20.86 years ($\pm$1.25*SD*) with an average height of 180.12 cm ($\pm$7.39*SD*), and average mass of 84.89 kg ($\pm$10.71*SD*) who were NCAA Division II college baseball pitchers participated. All participants had at least 1 season of pitching at the collegiate level, before testing. Each participant had undergone and passed a preseason medical examination performed by team doctors. At no time during this study were any of the participants under any medical supervision for conditions that would not allow for the normal biomechanics of a pitch. All participants were informed of risks, expectations, rules, and regulations of participation in the study. An explanation of the procedures and purpose of the study was given. Subjects were not required to participate and were free to remove themselves from the testing at anytime. The participants read and signed a University institutional review board approved written informed consent.

Procedures

Each pitcher underwent the same procedures in a repeated-measures design. Data were collected and used from the first 3 innings pitched, for each of the 3 recovery methods. That is, each pitcher was administered 1 recovery method for 3 innings on the same day. The next testing day the pitcher was administered a different form of recovery for all 3 innings. This was repeated again on the third testing day (Figure 1). To get an accurate measure of how the recoveries affected the pitchers, 3 forms of measurements were used. The difference BLa levels was used as a biological measurement, average

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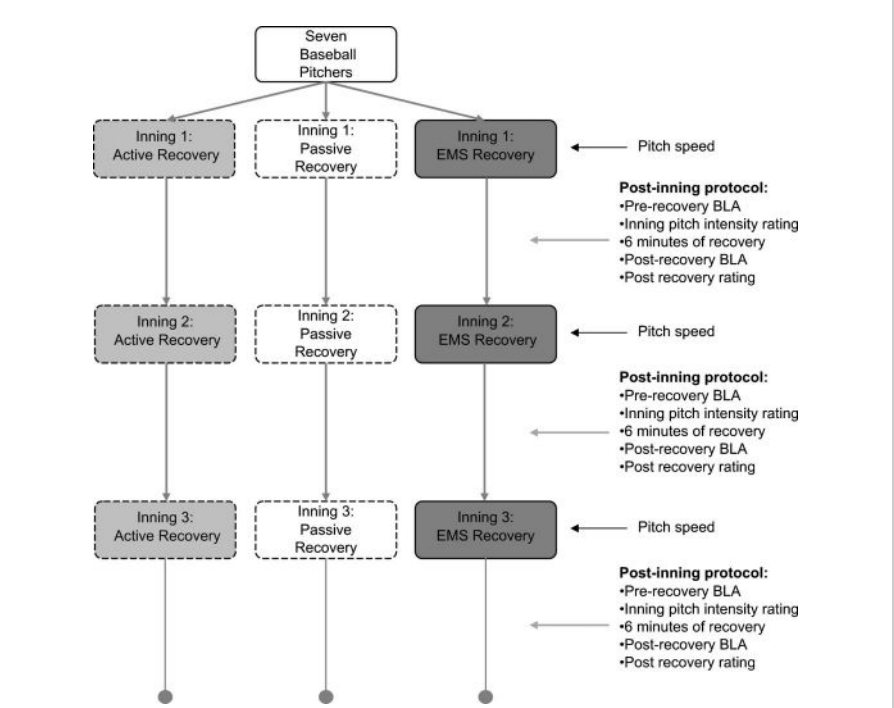

Figure 1. Overview of study design.

pitching speed was the physiological measurement, and the psychological measurement was done through the use of a scale to determine how the pitchers perceived their pitching and recovery. Subjects were tested at roughly the same time everyday and were instructed to maintain hydration levels as directed by their pitching coach.

The speed of every pitch was measured using a STALKER PRO Pitching speed radar gun (STALKER Professional Sports Radar, Applied Concepts, Inc., Plano, TX, USA), and the average speed for that inning was then calculated. Immediately after the inning ended, BLa was collected using a finger prick on the nonpitching hand. The Lactate Pro Blood Lactate Analyzer (Lactate Pro LT-1710, Arkray Factory, Inc., Shiga, Japan) was used to quantify the BLa levels. The study done by Pyne et al. found that the reliability of the Lactate Pro analyzer was $r = 0.99$ (12). Pitchers were also asked to rate their pitching intensity from that inning using a 0–10 scale with 0 indicating that the pitcher perceived no intensity in his pitching and 10 indicating that the pitcher gave the highest possible intensity for that inning. The form of recovery (AR, PR, or EMS) for the 6-minute recovery period was started immediately after BLa was collected. After the 6-minute period, BLa was collected again and the pitcher was asked to rate their recovery using a 0–10 scale with 0 indicating a feeling of no recovery and 10 indicating a feeling of full recovery (Figure 1).

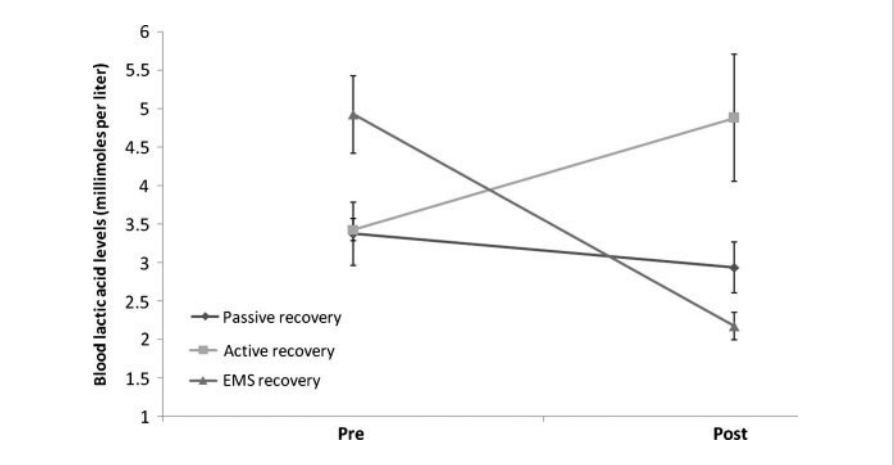

Figure 2. Mean blood lactic acid levels with standard error before and after treatment for each of the treatment conditions.

Passive Recovery. Passive recovery for this research was defined as sitting in the players' area with no activity for the 6-minute period. Pitchers were instructed to avoid any physical exertion during this 6-minute recovery period.

Active Recovery. The form of AR for this study was jogging for the 6-minute recovery period at approximately 60% of the estimated maximum heart rate, as predicted using the Karvonen method (third edition). The pitchers were instructed to gradually decrease their jogging intensity during the period to gradually reduce the heart rate.

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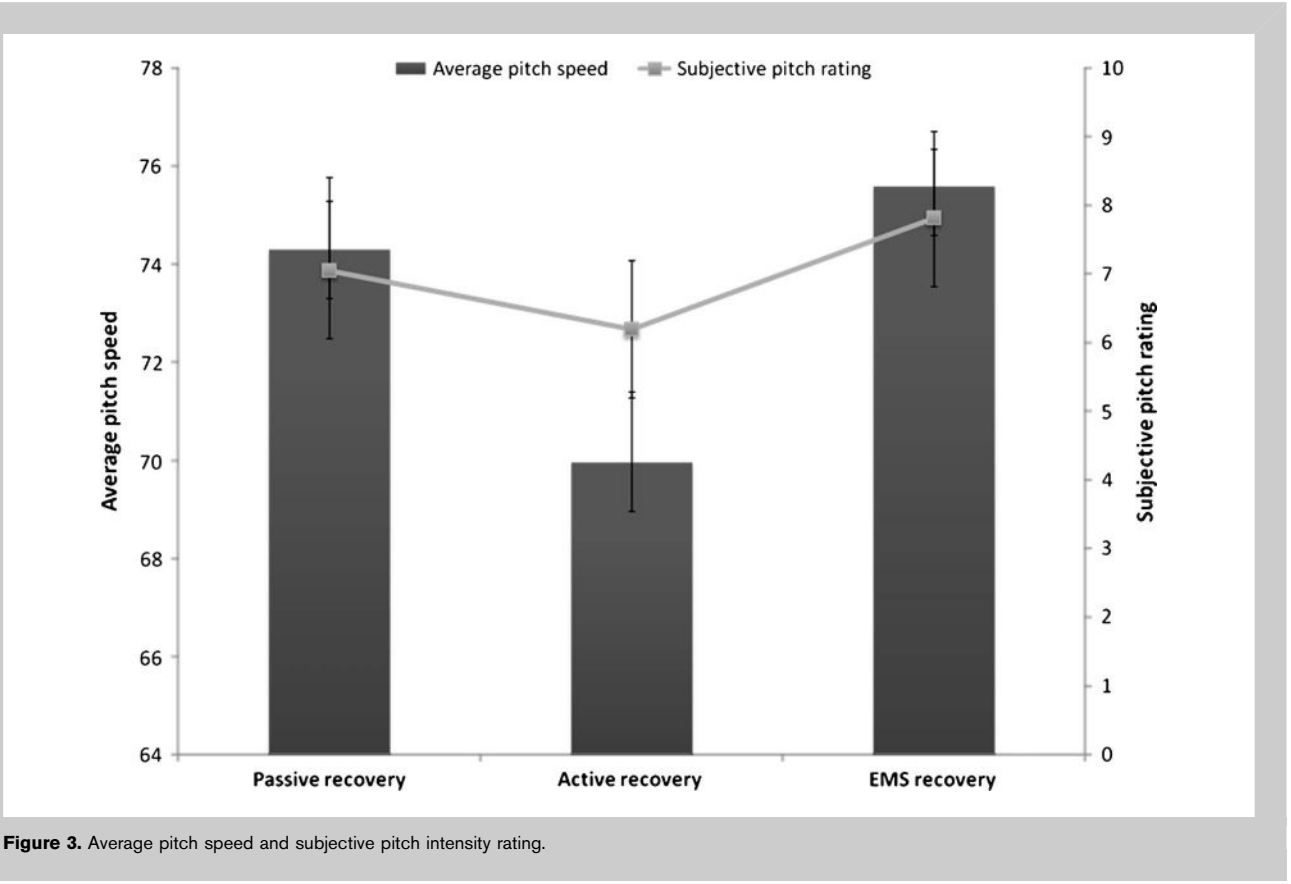

Figure 3. Average pitch speed and subjective pitch intensity rating.

The heart rate was to be decreased by about 15% every 2 minutes, with the final 2 minutes at approximately 30% of the pitchers estimated maximum heart rate (7,9,17).

Electromuscular Stimulation. The EMS unit that was used for this study was the Compex Sport unit (Compex Sport, Compex Technologies LLC, Ecublens, Switzerland). The participants received EMS recovery treatments using the "Active Recovery" setting, for a period of 6 minutes. The "Active Recovery" setting stimulates efferent motor neurons with a biphasic waveform. The specific setting was a rectangular biphasic symmetrical waveform, and the pulse width was 250 microseconds (1 microsecond $= 10^{-6}$ seconds). The program frequency started at 9 Hz and automatically decreased every 2 minutes. The first 2 minutes were at 9 Hz, the following 2 minutes were at 8 Hz, and the last 2 minutes were at 7 Hz (13,14). Six electrical leads were placed on the biceps brachii and triceps brachii muscle bellies; anterior and posterior deltoid; and anterior and posterior portions of the upper trapezius.

Statistical Analyses

A 2 (time: pre and post) × 3 (treatment: AR, PR, EMS) × 3 (inning: first, second, and third) analysis of variance (ANOVA) with repeated measures was conducted to determine differences in BLa levels between recovery conditions. An a priori alpha of 0.05 was used for significance. There was no 3-way interaction ($F(4,24) = 1.634$, $p = 0.244$, power = 23.9%). Likewise, there were no 2-way interactions for inning by time ($F(2,12) = 2.051$, $p = 0.171$, power = 34.0%) or inning by condition ($F(4,24) = 0.800$, $p = 0.421$, power = 12.6%). There was, however, a significant interaction for condition by time ($F(2,12) = 19.953$, $p \leq 0.0005$, $\eta_p^2 = 0.769$ (Figure 2). To break down this interaction, 5 simple main effects tests were conducted (i.e., 3 paired *t*-tests and 2 repeated measures ANOVAs) using a Bonferroni corrected alpha ($\alpha = 0.01$). Paired *t*-tests were used to determine if there was a significant difference in BLa levels before and after each of the treatment conditions. The ANOVAs were used to determine if the groups were different at pre and postmeasurement times. There were no significant differences over time for the PR condition ($p = 0.017$) or the AR condition ($p = 0.134$). However, there was a significant reduction in the EMS condition ($p \leq 0.0005$). There was a statistically significant difference between the groups before treatment ($p = 0.008$). Pairwise comparisons reveal that there was a significant difference between the PR condition and the EMS condition ($p = 0.020$). There was no significant difference between the EMS and AR conditions ($p = 0.087$) and between the AR and PR conditions ($p = 1.00$). There was no significant difference between the groups after the treatment ($p = 0.022$).

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To determine if the perceived recovery rate of the pitchers was consistent with the lactic acid levels, a repeated-measure ANOVA was conducted. The results demonstrated that there was a statistically significant difference ($F(2,12) = 6.989$, $p = 0.01$) among the 3 conditions: PR (mean = 7.43, $SD = 1.42$), AR (mean = 5.71, $SD = 0.78$), and EMS (mean = 8.00, $SD = 0.72$). Perceived recovery was greater for the EMS condition compared to the AR condition ($p = 0.006$) but not to the PR condition ($p = 212$). There was no difference between the PR condition and the AR condition in perceived recovery ($p = 1.00$).

Because 7 pitchers participated in game play situations (i.e., no regulation of the intensity and number of pitches) before the 3 different recovery conditions on 3 different days, it would be important to determine if their pitching intensity was consistent across the conditions. To do this, 2 repeated measures ANOVAs were conducted, 1 for average pitch speed during that inning and 1 for the pitchers' subjective rating of pitching intensity of the same inning. There was a statistically significant difference in average pitch speeds in the innings before treatment for the PR condition (mean = 74.29, $SD = 3.90$), AR (mean = 69.95, $SD = 3.78$), and the EMS (mean = 75.57, $SD = 2.97$), $F(2,12) = 54.047$, $p \leq 0.0005$. Pairwise comparisons revealed that the AR condition had a lower average speed compared to the other 2 conditions; ps $\leq$ 0.0005. There was no difference in speed between the AR and the EMS conditions; $p = 0.161$. The pitchers' subjective rating of their pitching intensity for the PR condition (mean = 7.05, $SD = 0.59$), AR (mean = 6.19, $SD = 1.18$), and the EMS (mean = 7.81, $SD = 1.00$) was significant and mirrored the pitch speeds in rank order, $F(2,12) = 7.832$, $p = 0.007$ (Figure 3). Pairwise comparisons revealed that the EMS condition had a greater pitch intensity than the AR condition, $p = 0.015$. The other 2 pairwise comparisons were not statistically different, ps $\geq$ 0.295.

Discussion

Results from this study suggest that recovery, in terms of reduction of BLa levels in the time between innings for baseball pitchers, was best for the EMS condition. The EMS was the only condition that had a significant decrease in BLa levels during this recovery period. There was no change in BLa acid levels for the AR and PR conditions. In addition, perceived recovery was best for the EMS and PR conditions. There was no difference between the AR and PR conditions for perceived recovery. Taken together, these results offer preliminary evidence that EMS is better than AR and PR which are both currently the most common modalities of recovery. Interestingly, it should be noted that in the inning before the recovery conditions, the most intense innings in terms of pitching speed and subjective ratings were the EMS and PR conditions, both of which counterintuitively faired better in measurements of recovery compared to the AR condition. In light of these current findings, future research regarding recovery with EMS using more rigorous methodology is warranted.

This study found that the AR was not beneficial to a baseball pitcher's speed or their perceived effort level, which is contrary to other studies. There was a significant decrease in the mean average speed to 70.0 mph, which correlated with a BLa increase of 1.452 mmol·L^{-1}, with the use of AR. The "tired" feeling may be explained by the decreased effective blood flow to replenish the glycogen stores (3).

With the short recovery time, PR caused the heart rate to decrease, so the lactic acid and by-products, including (H^+), were not eliminated as effectively. But, the pitcher is not using the glycogen stores that are left within the muscle to recover. So, there would not be any further depletion of glycogen stores within the muscle. There may actually be a slight increase as the lactic acid and by-products are cleared. The body may physiologically adapt to become more effective in the filtration of the blood during this recovery time, partially because there would not be a workload slowing biological processes down.

These findings are actually similar to other research that tested AR vs. PR in repeated-sprint cycles. Spencer et al. compared the use of AR and PR and found that despite no differences in the majority of performance measures, AR resulted in a significantly lower final peak power, a greater peak power decrement, suggesting a potential suboptimal effect of AR during repeated-sprint exercise (16). This information also supports the fact that AR and PR are not the most effective method of recovery for pitching. The AR and PR did not significantly reduce BLa levels. This too was consistent with their self-reported perception of recovery.

The studies that have been conducted with the use of EMS as a recovery technique were done as recovery method after aerobic endurance events. This is the first known research done to determine if the use of EMS as a recovery technique during anaerobic events is an effective technique. Further studies need to be done to find out if the 6-minute recovery period is the most effective amount of time for the baseball pitcher. The psychological aspects of the use of EMS may also play a role in the improvement found with its use.

The results of this study suggest that EMS is the most effective method of reducing BLa with a 6-minute recovery period between innings when compared to AR and PR. With the use of EMS, lactic acid level decreased by an average of 2.752 mmol·L^{-1}during the recovery period, indicating a reduction of H^+ and by-products; this mirrored the pitchers' perception of recovery. For some of the pitchers, their recovery lactic acid levels were lower than their initial levels. The EMS gave a mean decrease of 2.334 mmol·L^{-1} over the most common method of recovery, PR. The EMS had a superior decrease in the difference of 4.204 mmol·L^{-1} over AR.

These results suggest that the blood is being effectively cleared of the H^+ with the use of the EMS (20). This clearance would include an increase in the amount of new blood into the muscle. This new blood may include glycogen that would be able to be stored within the muscle more effectively because of

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the lack of the H^+ that may prevent storage (15). The EMS provides the benefits of AR without the cardio strain (13). This may allow the clearance of the muscle without the use of the glycogen stores to do the contractions (13). The increase in pitching speed may be accounted for by the increase in glycogen within the muscle (20). Also, it is possible that EMS may afford "rest" to the nervous system because muscle activation is mediated by direct electrical stimulation rather than cortical-mediated activation that occur during AR methods (20).

One limitation to this study was that in an attempt to allow for free game play, the pitching count and type of pitches were not tracked. This was done to try to prevent the pitchers from changing their normal pitching routine. Future studies should consider employing a more regulated pitching protocol so that the dosing of exertion is similar in all conditions. Another limitation was that the AR condition was not long enough to receive the full benefits of AR. The heart rate remained too high for the clearing of the blood and by-products. With the increase heart rate the liver's work rate is decreased. This also would inhibit the uptake of glycogen (20). The subject's medications and supplementations were not controlled. This may have had an effect on the clearance of the H^+ or uptake of glycogen. Another limitation was that the statistical power was strong enough to observer the 2-way interaction of condition by time; however, the overall design was underpowered for the 3-way interaction.

Practical Applications

We recommend that baseball pitchers consider employing EMS between innings to decrease BLa levels and to improve self-reported recovery, both of which may potentially lead to an increase in pitching performance. If EMS is not available, PR may help to improve perceived recovery; however, it is not effective for decreasing BLa levels. Based on our findings, we cannot confidently recommend AR as a method of recovery for baseball pitchers between innings.

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Electromyostimulation Training Effects on Neural Drive and Muscle Architecture

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ABSTRACT

GONDIN, J., M., GUETTE, Y. BALLAY, and A. MARTIN. Electromyostimulation Training Effects on Neural Drive and Muscle Architecture. *Med. Sci. Sports Exerc.*, Vol. 37, No. 8, pp. 1291–1299, 2005. **Purpose:** The purpose of the study was to investigate the effect of 4 and 8 wk of electromyostimulation (EMS) training on both muscular and neural adaptations of the knee extensor muscles. **Methods:** Twenty males were divided into the electrostimulated group (EG, $N = 12$) and the control group (CG, $N = 8$). The training program consisted of 32 sessions of isometric EMS over an 8-wk period. All subjects were tested at baseline (B) and retested after 4 (WK4) and 8 (WK8) wk of EMS training. The EMG activity and muscle activation obtained under maximal voluntary contractions (MVC) was used to assess neural adaptations. Torque and EMG responses obtained under electrically evoked contractions, muscle anatomical cross-sectional area (ACSA), and vastus lateralis (VL) pennation angle, both measured by ultrasonography imaging, were examined to analyze muscular changes. **Results:** At WK8, knee extensor MVC significantly increased by 27% ($P < 0.001$) and was accompanied by an increase in muscle activation (+6%, $P < 0.01$), quadriceps muscle ACSA (+6%, $P < 0.001$), and VL pennation angle (+14%, $P < 0.001$). A significant increase in normalized EMG activity of both VL and vastus medialis (VM) muscles (+69 and +39%, respectively, $P < 0.001$) but not of rectus femoris (RF) muscle was also found at WK8. The ACSA of the VL, VM, and vastus intermedius muscles significantly increased at WK8 (5–8%, $P < 0.001$) but not at WK4, whereas no changes occurred in the RF muscle. **Conclusion:** We concluded that the voluntary torque gains obtained after EMS training could be attributed to both muscular and neural adaptations. Both changes selectively involved the monoarticular vastii muscles. **Key Words:** STRENGTH GAINS, EMG ACTIVITY, MUSCLE ACTIVATION, HYPERTROPHY, KNEE EXTENSORS

The use of electromyostimulation (EMS) has been previously employed as a means of strength training in healthy humans (11,15–18,23,25). Many authors have indeed reported an increase in maximal voluntary contraction (MVC) following multiple EMS sessions (15–17,23,25), especially for the most often stimulated quadriceps femoris muscle (15,17,23,25). However, the underlying mechanisms responsible for this strength improvement remain unclear.

Several EMS studies have suggested that neural factors, rather than changes at the muscular level, largely account for the training-induced strength gains, particularly in the case of programs lasting 4 wk or less (16,18,25). For example, Maffiuletti et al. (16) reported a significant increase in plantar flexor MVC that was accompanied by an enhancement in both muscle activation and soleus electromyographic (EMG) activity following 4 wk of EMS training. Moreover, the dose–response relationship between quadriceps stimulation and activation of selected brain regions (26), but also cross-education effects (11) clearly demonstrated that EMS activated the neural system. All these findings indicated that neural adaptations probably occur after multiple sessions of involuntary resistance training.

Recently, Bickel et al. (4) showed that an acute bout of EMS was sufficient to stimulate molecular-level responses. Such changes indicated the initiation of hypertrophy processes in quadriceps muscle of both able-bodied and spinal cord–injured subjects. Thus, changes at the muscular level could also be expected after multiple sessions of EMS training. However, the effect of an EMS training program on muscle hypertrophy remains ambiguous in the literature, due mainly to the training duration adopted (19,24,25,27) and EMS parameters selected (24,27). For example, two studies (24,27) observed an impressive increase in quadriceps muscle size after 8–9 wk of EMS training, whereas others did not report such changes after EMS programs lasting 4 wk (19,25). It can, therefore, be hypothesized that muscle hypertrophy might occur as a result of an EMS training program lasting more than 4 wk.

The aim of the present study was to investigate the effects of 4 and 8 wk of EMS training on the neural and muscular properties of the knee extensor muscles, with particular emphasis on the time course of adaptations. To our knowledge, this study was the first to present a combined analysis of both muscular and neural factors after multiple sessions of EMS training. The EMG activity and muscle activation obtained during MVC of the knee extensor muscles were used to analyze neural adaptations. Torque and EMG responses obtained under electrically evoked contractions, muscle ACSA and vastus lateralis (VL) pennation angle, both measured by ultrasonography imaging, were assessed to study potential changes occurring at the muscle level.

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METHODS

Approach to the Problem and Experimental Design

This experiment was conducted to examine the neuromuscular adaptations induced by 4 and 8 wk of EMS training program of the knee extensor muscles. The EMG activity and muscle activation obtained under MVC was used to assess neural adaptations. Torque and EMG responses obtained under electrically evoked contractions, muscle anatomical cross-sectional area (ACSA) and VL pennation angle, both measured by ultrasonography imaging, were examined to analyze muscular changes. These variables were measured in two groups of subjects, one of which underwent a training program (i.e., electrostimulated group (EG)); the other received no exercise training (i.e., control group (CG)). The training program consisted of 32 × 18-min sessions of isometric (bilateral) EMS over an 8-wk period, with four sessions per week. All subjects were tested on four occasions: 2 wk (W-2) before baseline and at baseline (B) to assess interreliability measurements. Subjects were then retested after 4 (WK4) and 8 (WK8) wk of EMS training. Three to four days of rest separated the 16th and the 32nd training sessions from the WK4 and WK8 testing sessions, respectively. CG subjects were also retested after 4 and 8 wk of habitual daily activities. All measurements were carried out on the right leg. The independent variables were the time at which the measurement was taken (i.e., B, WK4, and WK8) and the group of subjects (i.e., EG and CG). Dependent variables were MVC, EMG activity and muscle activation obtained during MVC, evoked contractions (twitch and doublet stimulations) and associated maximal M wave, quadriceps and individual muscle ACSA, and VL pennation angle.

SUBJECTS

Twenty male students gave written informed consent to participate in this study. They were randomly assigned to EG, composed of 12 subjects (age 23.5 ± 5.0 yr, height 178.4 ± 8.9 cm, weight 73.7 ± 9.4 kg, means ± SD) or to CG (N = 8, age 24.3 ± 1.6 yr, height 176.4 ± 4.7 cm, weight 69.3 ± 7.4 kg, means ± SD). None of them had engaged in systematic strength training or EMS in the 12 months preceding the beginning of the experiments, but some were active in recreational sports. Approval for the project was obtained from the University of Burgundy committee on human research. All procedures used in this study were in conformity with the Declaration of Helsinki.

EMS Training

Training session. One week before the beginning of the stimulation period, the EG subjects participated in one practice session to familiarize themselves with stimulation parameters. The training program consisted of 32 × 18-min sessions of isometric (bilateral) EMS over an 8-wk period, with four sessions per week. Forty isometric contractions were carried out during each training session. During the stimulation, subjects were seated on a machine typically used for strength training of the quadriceps muscle (Multi-Form, La Roque D'Anthéron, France) with the knee joint fixed at a 60° angle (where 0° corresponds to full extension of the knee). Straps were consistently fastened across the pelvis to minimize hip and thigh motion during the contractions. Three 2-mm-thick, self-adhesive electrodes were placed over each thigh. The positive electrodes, measuring 25 cm^2 (5 × 5 cm), which had membrane depolarizing properties, were placed as close as possible to the motor point of the VL and vastus medialis (VM) muscles. The negative electrode measuring 50 cm^2 (10 × 5 cm) was placed 5–7 cm below the inguinal ligament. For each individual, the set of the electrodes was changed at the end of the fourth week of training. A portable battery-powered stimulator (Compex, Sport P, Medicompex, Ecublens, Switzerland) was used. Rectangular wave pulsed currents (75 Hz) lasting 400 μs were delivered with a rise time of 1.5 s, a steady tetanic stimulation time of 4 s, and a fall time of 0.75 s (total duration of the contraction: 6.25 s). Each stimulation was followed by a pause lasting 20 s (duty cycle: 24%). Intensity was monitored online and was gradually increased throughout the training session to a level of maximally tolerated intensity, which varied between 30 and 120 mA, according to the pain threshold of each subject. No subject reported serious discomfort. Each session was preceded by a standardized warm-up, consisting of 5 min of submaximal EMS at a freely chosen intensity (5 Hz, pulses lasting 200 μs). The stimulation characteristics of the present study were selected according to the recommendations of several authors (9,14). Such an EMS training protocol has been successfully used in our laboratory to increase knee extensor muscle strength (15,17).

EMS evoked force measurements. The individual level of isometric force developed during EMS was randomly measured using an isokinetic dynamometer once during the first 4 wk of training and once again during the last 4 wk of training with the testing position detailed below (see section on torque measurements). Subjects underwent the standardized warm-up EMS as described previously and then performed two MVC of the knee extensor muscles, separated by 2 min of rest. Subjects then completed the entire EMS training session and the evoked force was stored by means of commercially available software (Tida, Heka Elektronik, Lambrecht/Pfalz, Germany) for further analysis. The evoked force between the sixth and the 10th contractions were averaged and subsequently divided by the highest MVC obtained before the EMS training session. The force produced by EMS ranged indeed from 47 to 93% of the MVC (mean 68 ± 13%).

Measurements

Torque measurements. Instantaneous isometric torque at the knee joint was recorded using a Biodex isokinetic dynamometer (Shirley, NY). The subjects were placed in a seated posture with the trunk–thigh angle at 90°

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and the knee flexed at 60° (where 0° corresponds to the full extension of the knee), defined here as the training position. Each subject was securely strapped to the test chair with two crossover-shoulder harnesses and a belt across the hip joint. The axis of the dynamometer was aligned with the anatomical knee joint axis, and the lever arm was attached 2–3 cm above the lateral malleolus with straps. To allow biceps femoris EMG recordings, a board (thickness: 3 cm) was placed underneath the subject with a hole where the electrodes were placed so as to avoid any compression between the surface electrodes and wire on the seat. Subjects were asked to cross their arms during the testing procedure. Gravity correction was performed to account for the weight of the limb.

Electrical stimulation. The femoral nerve was stimulated using a cathode ball electrode (0.5 cm diameter) pressed and maintained by the same experimenter in the femoral triangle, 3–5 cm below the inguinal ligament. The anode was a large electrode (10 × 5 cm; Medicompex SA, Ecublens, Switzerland), located in the gluteal fold. Rectangular pulses of 1-ms duration were used, 400-V maximal voltage (Digitimer DS7, Hertfordshire, UK). The individual stimulation intensity was set by progressively increasing the stimulus intensity until there was no further increase in peak twitch torque (i.e., the highest value of the knee extensor twitch torque) nor in concomitant peak-to-peak M-wave amplitudes. This intensity was further increased by 20% (i.e., supramaximal intensity) and then maintained for single and paired stimulations (10-ms interspike interval). Individual supramaximal intensities were between 45 and 100 mA.

Experimental procedure. Testing procedure and recordings started with four single pulses each separated by 8 s, and three paired stimuli, each separated by 6 s, during which subjects were asked to relax. Then, subjects were instructed to perform two MVC of the knee extensor muscles. Paired stimuli were also delivered 3 s over the isometric plateau (superimposed doublet) and 3 s after the contraction (potentiated doublet) to assess muscle activation according to the twitch interpolation technique (1). Finally, two MVC of the knee flexor muscles were performed. The total duration of these efforts was approximately 5 s. A third knee extension and/or flexion MVC was performed if more than 5% difference was observed with respect to the highest MVC. A 3-min rest period was allowed between series of stimulations and between MVC to eliminate the effects of fatigue.

EMG recordings. Surface EMG activity of the VL, VM, rectus femoris (RF), and biceps femoris muscles was recorded bipolarly, during voluntary and electrically evoked contractions, by silver chloride circular electrodes with a diameter of 20 mm and a recording diameter of 10 mm. The electrodes were fixed lengthwise over the middle of the muscle belly with an interelectrode (center-to-center) distance of 20 mm. This site was determined in pilot testing by eliciting at a given intensity the greatest M-wave amplitude for each muscle via femoral nerve stimulation. This procedure was performed so as to avoid the innervation zone and therefore to obtain the optimal amplitude of EMG response. The reference electrode was attached to the patella of the contralateral leg. The placement of each electrode was marked on the skin with indelible ink, so that it could be exactly repositioned from session to session. Low resistance (<5 kΩ) between the two electrodes was obtained by abrading the skin with emery paper and cleaning with alcohol. EMG signals were amplified with a bandwidth frequency ranging from 15 Hz to 5.0 kHz (common mode rejection ratio = 90 dB; impedance = 100 MΩ; gain = 1000).

Data analysis. Mechanical and EMG traces were digitized online (sampling frequency 2 kHz) and stored by means of commercially available software (Tida, Heka Elektronik, Lambrecht/Pfalz, Germany). Only the highest knee extensor and knee flexor MVC were considered for analysis. MVC torque and EMG were analyzed over a 500-ms period once the torque had reached a plateau and before the superimposed stimuli. The root mean square (RMS) EMG values of VL, VM, and RF muscles were calculated and then normalized to the peak-to-peak amplitude of the maximal M wave (i.e., RMS/M ratio) for respective muscles. Muscle activation was estimated according to the following formula, that is, percent activation = (1 – superimposed doublet/potentiated doublet) × 100. The level of coactivation was calculated by normalizing the RMS values of the biceps femoris when this muscle was acting as an antagonist to the RMS obtained when this muscle was acting as an agonist, that is., during knee flexion, and was expressed as a percentage. Concerning the electrically evoked contractions, EMG and mechanical signals were averaged and peak-to-peak amplitude and duration of the VL, VM, and RF maximal M wave were measured. The following twitch contractile properties were analyzed: 1) peak twitch (Pt), the highest value of twitch torque production; 2) time-to-peak twitch (TPT), the time to obtain twitch maximal torque, calculated from the origin of the mechanical signal; 3) half-relaxation time (HRT), the time to obtain half of the decline in twitch maximal torque. For the paired stimuli, only the peak torque (Pt_{PS}) was measured.

Measurement of muscle ACSA. B-mode ultrasonography (Esaote Biomedica, AU5, Florence, Italy) with a 50-mm, 7.5-MHz linear-array probe was used to obtain axial-plane images of the quadriceps muscle, using previously applied methods validated in the VL muscle (21,22). All measurements were performed after the subjects had been in the supine position for at least 20 min to allow fluid shift to occur (3). During all measurements, the subjects were instructed to relax their leg muscles. Scans were taken in the axial plane at the level of 50% of the distance between the upper border of the superior patella and the greater trochanter. This position was marked on the skin with indelible ink. Orientated in the axial plane, the probe was aligned perpendicularly to the lateral side of the VL muscle and moved across a premarked section over echo-absorptive external markers fixed to the skin from a lateral to medial position. The probe was coated with a water-soluble transmission gel to provide acoustic contact. Great care was taken to consistently apply minimal pressure during scanning to avoid compression of the underlying structures.

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Scanning was recorded onto SVHS videotape and then acquired using frame-capture software (Adobe Premier version 5.1, Adobe Systems). Single scans were identified for further analysis. Using the lines cast by the external markers as references, scans were fitted using a contour matching program. All the scans were performed by the same investigator. The four individual muscles (VL, VM, RF, and vastus intermedius, i.e., VI) were measured separately by use of an image analysis program (NIH Image version 1.61, National Institutes of Health, Bethesda, MD). The mean of five consecutive morphometric analyses of each image was used to calculate $ACSA_{VL}$, $ACSA_{VM}$, $ACSA_{RF}$, and $ACSA_{VI}$. The mean ACSA of the quadriceps muscle ($ACSA_Q$) was then calculated by summing up the mean ACSA of the four individual muscles of the quadriceps. The image analyses were performed by a single investigator, who was blinded to the identity of the subject.

Measurement of muscle architecture. The pennation angle of the VL muscle was measured *in vivo* using real-time B-mode ultrasonography with a 50-mm, 7.5-MHz linear-array probe in the same condition described above (see Measurement of Muscle ACSA section). The width of the VL was measured at 50% of the length of the thigh and the center of the width was marked on the skin with indelible ink. At this position, the probe was positioned perpendicular to the dermal surface of the VL muscle and oriented along the median plane of the muscle. The probe was coated with a water-soluble transmission gel to provide acoustic contact without depressing the dermal surface. Pennation angle was defined as the angle between the fascicular path and the deep aponeurosis of the VL muscle. For each individual, four images at rest were obtained within the same experimental session. Data analysis was performed with the same digitizing software used for the ACSA determination. A mean of three pennation angles was assessed on each ultrasound image and thus a mean of 12 pennation angles was calculated.

Statistical analysis. To assess the interday (i.e., W-2 and B) and intraday (i.e., for individual muscle ACSA and for the pennation angle) variability of the present measurements, coefficients of variation (i.e., CV = SD/mean × 100) were calculated for each subject. The interday and intraday reproducibility of the variables was quantified with intercorrelation coefficients (ICC) based on repeated-measures ANOVA with testing session as the independent variable and on Cronbach's alpha, respectively. Normality of the data was checked and subsequently confirmed using the Kolmogorov–Smirnov test. Two-factor (group (EG vs CG) × session (B, WK4, WK8)) ANOVA with repeated measures on session were used to compare the dependent variables. When significant interactions were found, Tukey *post hoc* analysis was performed. Linear regression analysis (Pearson's product–moment correlation) was used to compare the degree of association between variables. Statistical power values were calculated for various significant differences and ranged from 0.329 to 0.931 (Table 1). Significance was accepted when $P < 0.05$. The statistical analyses were performed using Statistica software for Microsoft Windows (StatSoft, version 6.1, Tulsa, OK). All data are expressed as means ± SD in the text and as means ± SE in the figures.

TABLE 1. Statistical power associated with the two-way ANOVA repeated measures.

Variable	B-WK4	WK4-WK8	B-WK8
MVC	0.573	0.405	0.931
VL RMS/M	0.615	—	0.804
VM RMS/M	0.763	—	0.719
Muscle activation	0.432	—	0.631
KE ACSA	—	0.343	0.504
VL ACSA	—	0.329	0.493
VM ACSA	—	—	0.375
VI ACSA	—	0.339	0.386
Pennation angle	—	0.395	0.826

Data are presented when statistical significant differences ($P < 0.05$) were found ($N = 12$).

RESULTS

Reliability of measurements. Table 2 shows the interday reproducibility and variability of all the dependant variables. ICC and CV ranged from 0.799 to 0.964 and from 0.9% to 14.83%, respectively, except for the coactivation level (ICC = 0.680 and CV = 19.70%). Intraday reproducibility ranged from 0.995 to 0.999 and from 0.900 to 0.911 for ACSA and for the pennation angle, respectively. CV was between 0.53% and 0.95% and between 3.32% and 3.88% for ACSA and the pennation angle, respectively.

TABLE 2. Interday reproducibility (ICC) and variability (CV) between the two testing sessions (i.e., WK-2 and B) for respective variables ($N = 20$).

Variables	ICC	CV (%)
MVC		
Knee extensor (N·m)	0.868*	4.72
Knee flexor (N·m)	0.883*	4.78
EMG activity, activation, and coactivation		
RF RMS/M	0.824*	12.86
VL RMS/M	0.846*	12.67
VM RMS/M	0.799*	9.19
Biceps femoris RMS EMG (mVs)	0.906*	14.83
Muscle activation (%)	0.865*	3.21
Coactivation level	0.680**	19.70
Contractile properties		
Pt (N·m)	0.877*	6.39
TPT (ms)	0.957*	3.39
HRT (ms)	0.856*	6.40
Pt_{PS} (N·m)	0.895*	5.70
M-wave amplitude		
RF (mV)	0.873*	11.92
VL (mv)	0.888*	9.55
VM (mV)	0.851*	8.75
M-wave duration		
RF (ms)	0.940*	3.89
VL (ms)	0.888*	8.76
VM (ms)	0.940*	8.05
Muscle ACSA and muscle architecture		
RF (cm^2)	0.964*	1.82
VL (cm^2)	0.938*	1.72
VM (cm^2)	0.964*	1.60
VI (cm^2)	0.911*	1.78
Quadriceps (cm^2)	0.962*	0.95
Pennation angle (°)	0.812*	3.21

MVC, maximal voluntary contraction; EMG, electromyography; RMS, root mean square; RF, rectus femoris; VL, vastus laterlis; VM, vastus medialis; Pt, peak torque; TPT, time to peak twitch; HRT, half relaxation time; Pt_{PS}, peak twitch associated with paired stimuli; ACSA, anatomical cross-sectional area; VI, vastus intermedius.
* Significant at $P < 0.001$.
** Significant at $P < 0.01$.

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No significant baseline differences were observed between the two groups for any of the measured variables.

MVC, EMG activity, and activation level. Knee extensor MVC increased significantly between B and WK4 (+15 ± 11%, $P < 0.001$), between WK4 and WK8 (+11 ± 11%, $P < 0.001$) and between B and WK8 (+27 ± 15%, $P < 0.001$) in the EG (Fig. 1A). No significant changes in MVC of the knee extensor muscles occurred in the CG (238 ± 49, 233 ± 44, and 244 ± 46 nm at B, WK4, and WK8, respectively).

Muscle activation increased significantly in the EG between B and WK4 (+5 ± 6%, $P < 0.05$, Fig. 1B) and between B and WK8 (+6 ± 6%, $P < 0.01$). No significant changes were observed in muscle activation in the CG (88 ± 8%, 87 ± 7%, and 89 ± 6% at B, WK4, and WK8, respectively).

Significant group × session interactions ($P < 0.01$, Fig. 2A and B) were found for VL and VM but not for RF RMS/M ratio ($P > 0.05$, Fig. 2C). In the EG, VL and VM RMS/M ratios increased significantly between B and WK4 (+44 ± 19% and +42 ± 31%, respectively, $P < 0.05$) and between B and WK8 (+69 ± 56% and +39 ± 25%, respectively, $P < 0.001$) (Fig. 2A and B). No significant changes in VL and VM RMS/M ratios occurred in the CG (Fig. 2A and B).

A significant negative correlation (r = 0.720, $P < 0.01$; statistical power: 0.777), fitted with a linear function, was found between the muscle activation values at baseline and the MVC relative gains between B and WK8 (Fig. 3). This relationship showed that the lower the voluntary activation level was, the greater the strength gains.

There was no interaction for group × session ($P > 0.05$) for MVC of the knee flexor muscles nor for biceps femoris RMS values. Knee flexor MVC for B, WK4, and WK8 were 122 ± 23, 135 ± 29, and 131 ± 34 nm in the EG and 118 ± 21, 119 ± 10, and 122 ± 19 nm in the CG, respectively. Biceps femoris RMS values for B, WK4, and WK8 were 0.15 ± 0.06, 0.15 ± 0.06, and 0.17 ± 0.08 mV in the EG and 0.15 ± 0.07, 0.17 ± 0.09, and 0.14 ± 0.07 mV in the CG, respectively.

No significant group × session interaction was observed for the level of coactivation ($P > 0.05$). The level of coactivation for B, WK4, and WK8 were 9.0 ± 3.9, 10.1 ± 4.5, and 10.0 ± 3.3% in the EG and 8.1 ± 3.1, 7.8 ± 4.2, and 9.0 ± 3.4% in the CG, respectively.

Contractile properties and M waves. No significant group × session interactions were noted for Pt, TPT, HRT, or Pt_{PS} ($P > 0.05$, data not shown) nor for either M-wave amplitude or duration in the three muscles ($P > 0.05$, data not shown).

Muscle size. In the EG, $ACSA_Q$ increased significantly between WK4 and WK8 (+4 ± 2%, $P < 0.001$, Fig. 1C) and between B and WK8 (+6 ± 2%, $P < 0.001$), whereas a trend toward a significant increase was observed between B and WK4 (+2 ± 2%, $P = 0.06$). Within the individual muscles of the quadriceps, a significant group × session interaction was observed for the VL, VM, and VI muscles ($P < 0.001$), but not for the RF muscle ($P > 0.05$,

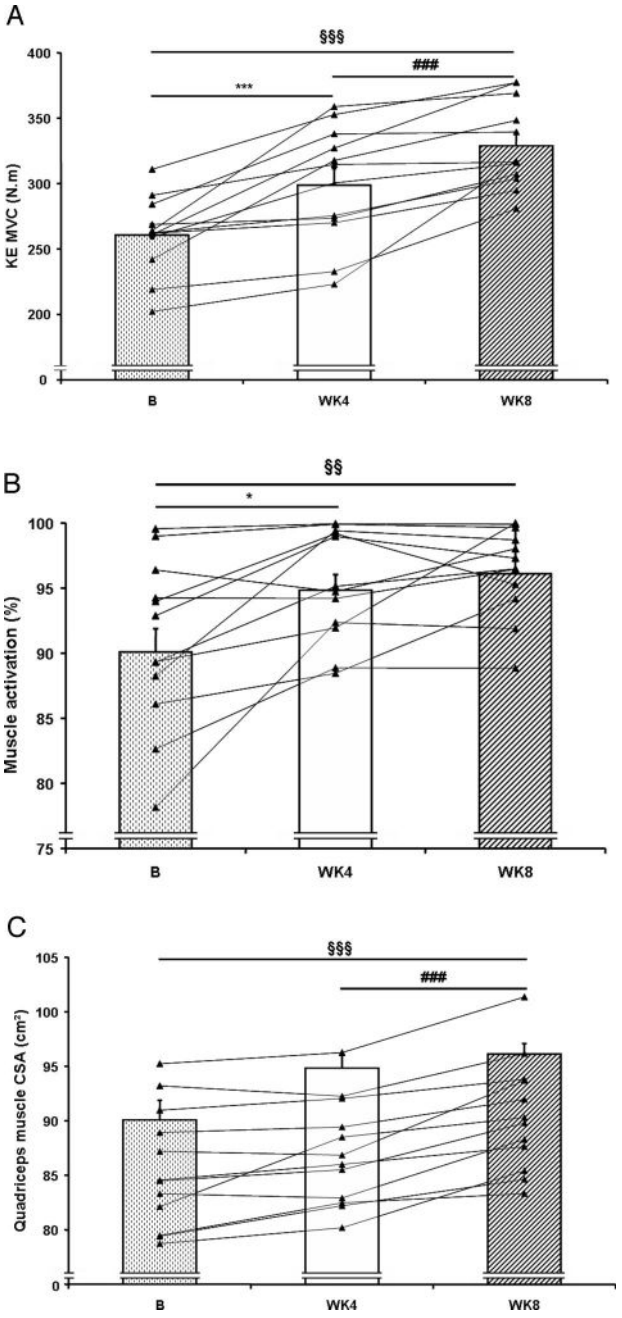

FIGURE 1—(A) Maximal voluntary torque produced by the knee extensor (KE) muscles at baseline (B), following the 4-wk (WK4) and 8-wk (WK8) period for the electrostimulated group (EG, $N = 12$). (B) Knee extensor maximal muscle activation for the electrostimulated group (EG, $N = 12$), at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) periods. (C) Quadriceps muscle ACSA measured at 50% of the distance between the upper border of the superior patella and the greater trochanter by use of ultrasonography imaging, at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) period in the electrostimulated group (EG, $N = 12$). Data were obtained by the addition of the mean ACSA of the four individual muscles of the quadriceps. Triangle symbols and columns show individual values and group mean values, respectively. SE is indicated by error bars. Significant difference between B and WK4 conditions: *$P < 0.05$; ***$P < 0.001$. Significant difference between WK4 and WK8 conditions: $^{\#\#\#}P < 0.001$. Significant difference between B and WK8 conditions: $^{\S\S}P < 0.01$; $^{\S\S\S}P < 0.001$.

Table 3). In the EG, $ACSA_{VL}$ and $ACSA_{VI}$ increased significantly between WK4 and WK8 (+5 ± 6% and + 5 ± 3%, respectively, $P < 0.001$) and between B and WK8 (+8

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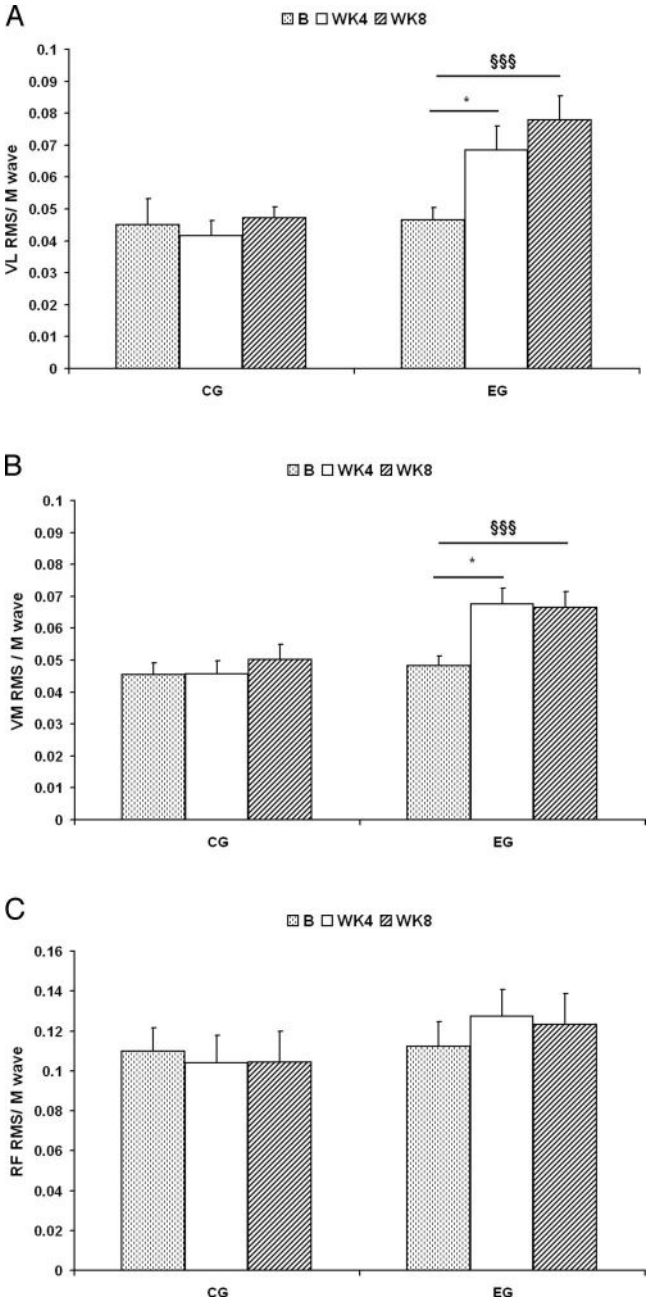

FIGURE 2—Normalized EMG activity (RMS/M ratio) for respective muscles obtained during maximal voluntary knee extension, at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) periods for the control group (CG, $N = 8$) and the electrostimulated group (EG, $N = 12$). (A) VL, (B) VM, (C) RF. All values are means ± SE. Significant difference between B and WK4 conditions: *$P < 0.05$. Significant difference between B and WK8 conditions: §§§ $P < 0.001$.

± 5% and +6 ± 4%, respectively, $P < 0.001$). In the EG, $ACSA_{VM}$ showed a trend toward a significant increase between WK4 and WK8 (+3 ± 3%, $P = 0.07$), whereas a significant increase was observed between B and WK8 (+5 ± 5%, $P < 0.001$). $ACSA_Q$ (82 ± 4 cm^2, 82 ± 5 cm^2, and 82 ± 4 cm^2 at B, WK4, and WK8, respectively), $ACSA_{VL}$, $ACSA_{VI}$, and $ACSA_{VM}$ remained unchanged in the CG.

Muscle architecture. In the EG, the VL pennation angle increased significantly between WK4 and WK8 (+7 ± 7%, $P < 0.05$, Fig. 4) and between B and WK8 (+14 ±

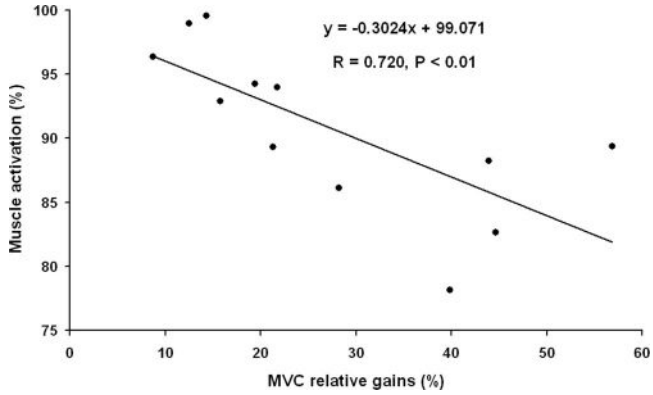

FIGURE 3—Individual data of knee extensor maximal voluntary contraction (MVC) relative gains between baseline and 8-wk period conditions plotted against maximal muscle activation values at baseline for the EG ($N = 12$). Data are fitted with a linear regression function.

7%, $P < 0.001$), whereas a trend toward a significant increase was observed between B and WK4 (+6 ± 8%, $P = 0.06$). No significant changes in the pennation angle were observed in the CG (Fig. 4).

It should be noted that all 12 subjects showed an increase in the main parameters between B and WK8, namely, knee extensor MVC (which ranged from 9% to 57%), muscle activation (which ranged from 1% to 18%), and quadriceps muscle ACSA (which ranged from 3% to 10%).

DISCUSSION

Although EMS has been largely employed as a means of strength training, the physiological adaptations by which EMS increases voluntary strength have been poorly investigated. This study demonstrated that the significant increase in quadriceps muscle MVC observed after 8 wk of EMS training was accompanied by a significant increase in 1) muscle activation, 2) normalized EMG activity of the VL and VM muscles but not of the RF muscle, 3) quadriceps muscle ACSA, and 4) VL fiber pennation angle. The data also indicated that 1) neural adaptations mainly occurred during the first 4 wk of EMS training, whereas changes in muscle mass and architecture became significant between weeks 4 and 8 of the training program and 2) both neural and muscular adaptations mainly affected the monoarticular vastii and not the biarticular RF muscle.

Reliability measurements. The variables considered in the present study demonstrated a low variability (CV < 15%) and a high degree of reproducibility (ranging from 0.799

TABLE 3. Individual muscle ACSA at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) period for the control group (CG) and the electrostimulated group (EG).

	CG			EG		
	B	WK4	WK8	B	WK4	WK8
VL (cm^2)	28.4 ± 2.0	27.8 ± 2.0	28.1 ± 1.6	28.4 ± 2.2	29.0 ± 1.9	30.6 ± 2.6*†
VI (cm^2)	27.9 ± 1.9	27.6 ± 1.9	27.8 ± 1.8	28.4 ± 2.3	28.7 ± 2.4	30.1 ± 1.9*†
VM (cm^2)	15.0 ± 1.4	15.1 ± 1.1	15.0 ± 1.2	16.6 ± 1.2	16.9 ± 1.2	17.4 ± 1.0†
RF (cm^2)	11.2 ± 0.8	11.3 ± 0.8	11.2 ± 0.8	12.2 ± 1.2	12.4 ± 1.1	12.5 ± 1.3

VL, vastus lateralis; VI, vastus intermedius; VM, vastus medialis; RF, rectus femoris. CG: $N = 8$; EG: $N = 12$. All values are means ± SD. * $P < 0.001$, significant difference between WK4 an WK8 conditions. † $P < 0.001$, significant difference between B and WK8 conditions.

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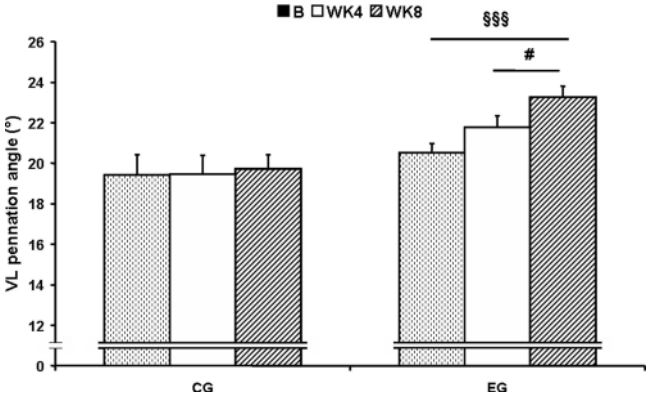

FIGURE 4—The vastus lateralis (VL) muscle fiber pennation angle obtained at 50% femur length by use of ultrasonography imaging, at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) periods for the control group (CG, $N = 8$) and the electrostimulated group (EG, $N = 12$). All values are means ± SE. Significant difference between WK4 and WK8 conditions: $^{\#}P < 0.05$. Significant difference between B and WK8 conditions: $^{\S\S\S}P < 0.001$.

to 0.964) between two different testing sessions (i.e., W-2 and B). According to Stokes (28), CV lower than or equal to 15% could be considered acceptable in biological systems. Moreover, similar CV and ICC values have been reported in the literature for MVC (29), muscle activation (1,29), muscle ACSA (21,22) and the VL pennation angle (8).

Maximal muscle strength. An average increase of 27% in MVC of the knee extensor muscles was observed after 8 wk of EMS training. These results are consistent with those reported in the literature after EMS training of the quadriceps muscle in healthy humans (15,17,23). Another interesting finding of the current study is the correlation observed between baseline muscle activation values and the strength gains at the end of EMS training, which indicated that muscle activation might be considered as an index of training status, where the lower activation values at baseline are associated with the greater training-induced gains in MVC strength. Thus, the present study demonstrated, at least for EMS training, that the lower the muscle activation was, the greater the strength gains.

Time course of neural versus muscular changes. This study was the first to report the time course of neural and muscular changes following multiple sessions of involuntary training. The gains in maximal voluntary strength observed at the end of the present EMS training program are attributable to both muscular and neural adaptations (see Fig. 1). After the first 4 wk of training, muscle activation significantly increased, whereas a trend toward a significant increase in both muscle ACSA and the VL pennation angle was observed. These results are in accordance with Maffiuletti et al. (16), who reported an increase in both muscle activation and soleus EMS activity after 4 wk of EMS training on the plantar flexor muscles, whereas Martin et al. (19) did not observe changes in muscle mass when using the same training program. Moreover, our results also showed that after 8 wk of EMS training, changes in muscle mass and architecture became significant and muscle activation was still higher than at baseline. To our knowledge, only a few studies (24,27) have used an EMS training program lasting 8 wk or more in healthy humans, and they reported impressive quadriceps muscle hypertrophy in agreement with the present study. Thus, by using a combined analysis of both muscular and neural factors after 4 and 8 wk of an EMS training program, our results clearly demonstrated that neural adaptations account for the initial voluntary strength improvement, whereas muscular changes took part in the further increase in strength.

Neural adaptations. In the present study, two different methods were used to assess neural adaptations of the knee extensor muscles. Muscle activation estimated by using the twitch interpolation technique significantly increased by 6% after training, thus indicating that EMS training enhanced the overall activity of the quadriceps muscle. These results are in agreement with those reported by Maffiuletti et al. (16) on the plantar flexor muscles after 4 wk of EMS training. Such activation increases could be ascribed to changes occurring at the supraspinal but also at the spinal level. Indeed, EMS evokes action potentials in both intramuscular nerve branches (12) and cutaneous receptors, thus inducing force production directly by activation of motor axons and indirectly by reflex recruitment of spinal motor neurons (5). However, a previous study performed in our laboratory (16) found no changes in resting soleus H-reflex amplitude after 4 wk of EMS training, therefore suggesting that the mechanisms accounting for the strength gains could be an increased volitional drive from the supraspinal centers. This last suggestion is reinforced by the study of Smith et al. (26), who reported that EMS applied over the quadriceps femoris muscle activated specific neural regions in a dose–response manner. However, further research is warranted to accurately determine the neural mechanisms responsible for the voluntary strength improvement.

Although muscle activation values observed in this study are in accordance with those previously reported in the literature (2), the twitch interpolation technique does not permit an investigation of the activation of individual muscles and thus the potential selective effect of EMS training on monoarticular vastii as opposed to biarticular RF muscle. The RMS EMG values obtained during MVC were indeed normalized to the respective M wave to better characterize neural activation of each muscle composing the quadriceps femoris. Both VL and VM EMG activity significantly increased, whereas no changes were observed for the RF muscle following 8 wk of EMS training. Similar to the present findings obtained on the monoarticular vastii muscles, EMG activity from the soleus muscle has been found enhanced following 4 wk of EMS training (16). On the other hand, it is not surprising to observe that RF EMG activity was not significantly higher after our single-joint EMS training program because this muscle was not directly stimulated by the electrodes during the training sessions. Despite the relatively high coefficient of variation in RMS/M ratios (12%) and the limits of EMG signal extraction (7), our results were corroborated by the fact that all 12 subjects showed an increase in muscle activation at the end of the training program.

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Muscular changes. This study demonstrated a significant increase of quadriceps muscle ACSA with EMS training in healthy humans. The absolute values at baseline (80–85 cm^2) are consistent with those reported in the literature (20). Due to the length of time scanning and data analysis associated with the ultrasonography imaging method, only a single ACSA was performed in the midregion of the muscle, and this might result in an overestimation of the increase in ACSA (22). However, this technique has been recently demonstrated as valid and reliable in detecting changes in muscle size (21,22).

Thus, the increase in muscle ACSA observed after our EMS training could be ascribed, at least in part, to changes at the muscular level, which is in line with the observations of Bickel et al. (4). Indeed, these authors recently showed that an acute bout of EMS was sufficient to stimulate a molecular-level response, which indicated the initiation of hypertrophy processes in quadriceps muscle of able-bodied subjects. Nevertheless, the mean changes in muscle ACSA observed in our study were lower (6% vs 10%) than those previously reported in the literature (24,27). However, these two studies (24,27) stimulated the quadriceps muscle during both lengthening and shortening actions, whereas our EMS protocol involved isometric contractions. Despite such discrepancies, our results demonstrated that multiple sessions of EMS training induced quadriceps muscle hypertrophy.

B-mode ultrasonography provides sufficient image quality to allow delineation of individual muscles (21), and in the present study, the ACSA of the four constituent muscles of the quadriceps was measured separately. These values are very similar to those reported in the literature for the same scanning region (20). The ACSA of the three vastii muscles (i.e., VI, VL, and VM) increased significantly (5–8%), but no changes were observed for the RF muscle after the 8 wk of EMS training. The EMS protocol involved isometric contractions at a knee joint angle of 60°. Herzog et al. (10) demonstrated, from force-length relations assessed on human cadavers, that the individual force produced by the three vastii muscles reached their maximal values at the angle considered in our study, whereas only a small force production was obtained for the RF muscle. Thus, the amount of stimulation provided during training on the quadriceps muscle might have induced high tension on the monoarticular vastii muscles but not on the biarticular RF, therefore resulting in selective hypertrophy. The findings of the current study indicated that both neural and muscular adaptations occurred mainly on the monoarticular muscles, suggesting that such preferential individual muscle hypertrophy might be dependent on the selective enhancement of the neural drive to these muscles. Although the statistical power values for both quadriceps and individual (i.e., VL, VM, VI) muscle ACSA were not high enough, the quadriceps muscle ACSA increased in all 12 subjects after the 8-wk EMS training program.

The VL pennation angle values reported before training are in accordance with those observed by Fukunaga et al. (8) in the same testing conditions (i.e., 19–20°). This study is the first to report that EMS training resulted in a marked increase (14%) of the VL pennation angle. Thus, the 14% increase in the pennation angle would allow the concentration of a large number of contractile elements along the tendon (13). Also, the steeper muscle fiber pennation angle might largely contribute to the increase in muscle ACSA and thus play a role in the strength gains observed at the end of the EMS training program.

The analysis of the mechanical and electrical (i.e., M wave) twitch parameters evoked at rest by single and paired supramaximal electrical stimulation provide an indication of changes in excitation-contraction coupling. In the present study, none of these properties was altered as a result of training. The fact that 8 wk of EMS training did not affect excitation-contraction coupling properties is in line with prior results obtained on the triceps surae (16) and adductor pollicis muscle (6) following 4–6 wk of EMS training.

Practical applications of EMS training. The results of the present study clearly demonstrated that EMS training programs may induce both neural and muscular adaptations in healthy humans. Thus, the benefits of EMS should be useful in the design of rehabilitation programs to minimize the loss of quadriceps muscle function before, during, and after an immobilization period. Furthermore, considering the linear relationship between baseline muscle activation values and strength gains at the end of EMS training, muscle activation might provide an useful index of strength gains, at least in intact systems.

In conclusion, the present study demonstrated that neural as well as muscular adaptations are responsible for the quadriceps MVC torque increment obtained after 8 wk of EMS training. The former mainly accounted for the larger proportion of initial strength increment, whereas the latter took part in the further increase in strength. Both neural and muscular changes affected mainly the monoarticular vastii rather than the biarticular RF muscle, probably due to the specificity of muscle solicitation.

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Neuro-Muscular Electrical Stimulation Training Enhances Maximal Aerobic Capacity in Healthy Physically Active Adults.

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Abstract — **Previous research has shown that a novel form of neuro-muscular electrical stimulation (NMES) can be used to bring about aerobic training effects in sedentary adults and in patients with heart failure. However, it is not clear whether this form of NMES could induce a significantly strong cardiovascular exercise effect in a more active group where a greater stimulus is required for training. In this study we investigated the aerobic training effects of repeated exposure to low frequency NMES in a group of physically active healthy adults. Results demonstrated a clinically and statistically significant training response following 18 trainings sessions, suggesting that this form of NMES has a role to play in cardiovascular exercise training in a physically active healthy population.**

I. INTRODUCTION

Neuro-muscular electrical stimulation (NMES) has been used in health and sport for many years as a means of augmenting voluntary exercise programmes to re-educate and strengthen muscle skeletal muscle [1]. However, in recent years there has been a growing awareness of the potential for using NMES as a training modality in management of diseases associated with inactivity and reduced cardiovascular exercise capacity. Researchers have demonstrated that repeated exposure to NMES can bring about improvements in measures of exercise capacity and functional status in patients with chronic obstructive pulmonary disease and heart failure [2]. The NMES applications in these studies have typically incorporated stimulation parameters that elicit tetanic isometric contractions of the large lower limb muscle groups with a duty cycle of 5-7s on and off.

We have developed a new approach to cardiovascular training using NMES that involves using low frequency stimulation to elicit a pattern of rhythmical contractions of the large leg muscle groups at sub-tetanic frequencies. Initial investigations demonstrated that the physiological effect of acute exposure to this form of NMES is similar to the physiological response to regular cardiovascular exercise such as jogging or cycling [3]. Furthermore, there is evidence of a repeatable dose-response relationship with increases in stimulation intensity resulting in increases in physiological cost as evidenced by heart rate, respiratory rate and oxygen consumption [4].

Subsequent training studies revealed that repeated exposure to this form of low frequency NMES over a period of 6-weeks resulted in significant improvements in maximal aerobic capacity, 6 minute walk distance and quadriceps strength in separate studies on sedentary adults [5] and patients with chronic heart failure [6]. These results indicate that this form of NMES induced cardiovascular exercise has significant potential as an alternative exercise modality in patient cohorts in whom traditional forms of exercise may be difficult and for whom a relatively low training stimulus is required. Its potential as an alternative exercise modality in a physically active population in whom greater training stimulus is needed to bring about improvements in physical fitness is less certain. We have recently demonstrated that acute exposure to this form of NMES results in a cardiovascular exercise response that is consistent with the low end of the therapeutic training intensity spectrum (50-80% of VO2max) for a physically active population as recommended by the American College of Sports Medicine [7]. The purpose of the present investigation was to determine whether repeated exposure to this form of low frequency NMES would provide sufficient training stimulus to effect an improvement in maximal aerobic capacity in a young, physically active population.

II. METHOD

Subjects.

Nineteen healthy adult subjects (14m, 5f) volunteered to participate in this study. The institutional Ethics Committee approved the study and written informed consent was obtained in all cases. The subjects had a mean age of 32.6 ± 10.6 years and an average mass and body mass index (BMI) of 79.6 ± 16.1 kg and 25.1 ± 4.2 kg/m^2 respectively. All subjects were recruited within the University, were free from illness or injury, and were physically active in recreational activities at the time of participation in the study.

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Potential Conflict of Interest Disclosure - C Minogue is an employee of the manufacturer of the stimulation device used in this study.

Study Design.

This was a prospective case control study in which we followed each subject for a period of 10 weeks with 3 measurement points in each case. Measures of maximal aerobic capacity were taken at baseline, following a 4 week period in which subjects adhered to their habitual activity patterns (control phase), and following 6 weeks of habitual activity supplemented with 18 1-hour sessions of low frequency NMES training (training phase).

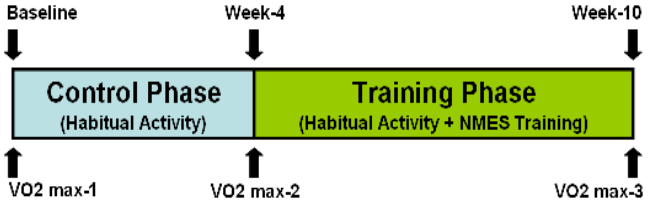

Figure 1. Study Design

Aerobic Testing Procedures.

Maximal aerobic exercise capacity was evaluated using an incremental cycle ergometer test protocol with simultaneous cardiopulmonary gas exchange analysis. Subjects wore a facemask and a gas analysis system (Quark b^2, Italy) was used to measure the expired oxygen and carbon dioxide concentration and volume. $V'O_2$ was calculated from these measurements. Subjects were required to pedal at incremental workloads until a leveling of $V'O_2$ response despite increasing exercise intensity occurred. $V'O_2$ max was calculated from the average $V'O_2$ measurement during the last 30 seconds of the cycle test at each test session. Heart rate (HR) was also recorded throughout the test and the workload (Watts) at the end of each test was noted. The maximal aerobic test was carried out by the same investigator at baseline, and following the control and training phases of the study.

Stimulation Protocol.

A specially designed hand held muscle stimulator (NT2010, BioMedical Research Ltd, Galway, Ireland) was used to produce rapid rhythmical contractions in the large lower extremity muscle groups in this investigation. The stimulator current waveform was designed to produce rhythmical contractions in the lower extremity muscle groups. These contractions were achieved by means of delivering a burst of 4 mixed frequency pulses at a beat frequency of 5Hz. The maximum peak output pulse current used in the present study was 200 mA. Impulses were delivered through an array of 4 adhesive electrodes on each leg (area per leg = 800 cm^2), with a different combination of electrodes from the array being involved in delivery of each of the 4 pulses in a burst. The current pathways, electrode combinations per pulse and pulse train characteristics are outlined in Figure 2. The electrode arrays were applied to the body via a neoprene 'wrap' garment that was secured to the thigh with Velcro straps. This array of electrodes produced rhythmical contractions in the quadriceps, hamstrings, and calf muscles. This rhythmical pattern of muscle contraction was associated with an increase in oxygen tissue in the tissues and resulted in a physiological response consistent with cardiovascular exercise in the absence of limb loading or the need to perform external work.

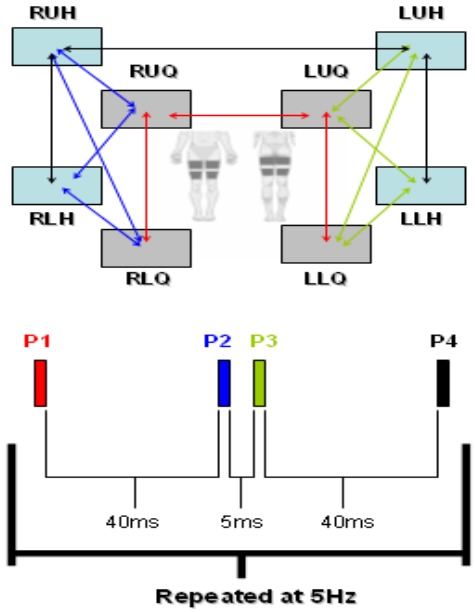

Figure 2. Location of Stimulating Electrodes, pulse pathways (color coded), and pulse intervals. RUQ – right upper quadriceps, RUH – right upper hamstring, RLQ – right lower quadriceps etc)

Training Protocol.

During the training phase all subjects were required to complete a total of 18 separate NMES sessions of 1-hour duration each. All sessions were performed in the University. The subjects were not directly supervised throughout each session but a record of their attendance was kept by the main investigator throughout the study period. Further to this, each subject kept a log of their training in which they recorded subjective feedback and the stimulation intensities reached during each session. During each session subjects performed a gradual warm-up and cool down during the first and last 10 minutes with a 40 minute period at their training intensity. Subjects were instructed to select a stimulation intensity that resulted in a subjective increase in rate of perceived exertion (RPE) to the 'somewhat hard' level [8]. RPE was used to govern exercise intensity due to previous work that demonstrated that V'O2 response and RPE were linearly related with low frequency NMES induced exercise in a manner similar to the relationship observed during voluntary exercise [7].

Data Analysis.

$V'O_2$ max and maximal exercise test workload values were identified for each subject for each time point – baseline, week 4 and week 10. The difference between $V'O_2$ max at week 4 and baseline was calculated for each subject and represented the Control Response. The difference between $V'O_2$ max at week 10 and week 4 was calculated for each subject to derive the NMES Training Response.

To test for statistical significance, separate repeated measures ANOVA F-tests were carried out to determine whether differences existed between group mean $V'O_2$ max or maximal exercise test workload at each measurement interval during the study. This was followed up with post hoc paired 2-sided t-tests performed to test for differences between baseline and week 4, week 4 and week 10 and baseline and week 10 respectively. Finally, paired, 2-sided t-tests were carried out to test for differences between group average control and NMES training responses. All statistical analysis was performed using SPSS software (V12.0).

III. RESULTS.

All subjects completed the test procedures without any difficulty and all completed the 18 training sessions as prescribed. ANOVA F-test analyses revealed highly significant differences in both $V'O_2$ max and maximal exercise test workloads across the 3 test conditions ($P<0.0001$). Post hoc analysis indicated that there were no significant differences between group mean $V'O_2$ max levels or maximal exercise test workloads at baseline and at 4 week follow up ($P>0.05$). However, there were highly significant differences between both $V'O_2$ max levels and maximal exercise test workloads at 10 week follow up compared to both baseline and 4 week follow up ($P<0.005$). We also observed significant differences between the group mean Control and NMES Training responses for $V'O_2$ max ($P<0.05$) (Figure 3). Group mean (±SD) $V'O_2$ max was 42.3±6.6 ml/kg/min at baseline. This remained largely unchanged at 4 weeks at 42.9±6.8ml/kg/min yet increased to 45.8±6.4ml/kg/min at 10 week follow up (Figure 4). Group mean (±SD) maximal exercise test workloads were 253.7±48.6 and 253.7±49.2Watts at baseline and 4 week follow-up respectively. This increased to 265.4±57.7Watts at 10 week follow-up (Figure 5).

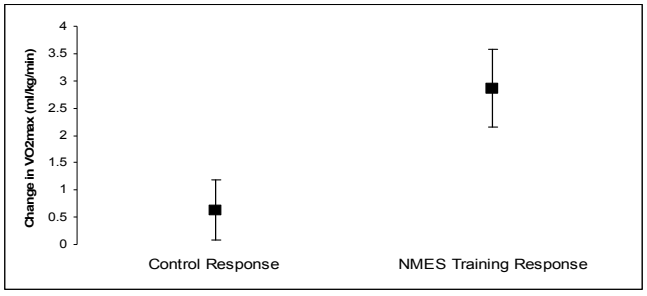

Figure 3. Average (±SE) Control and NMES $V'O_2$ max training responses.

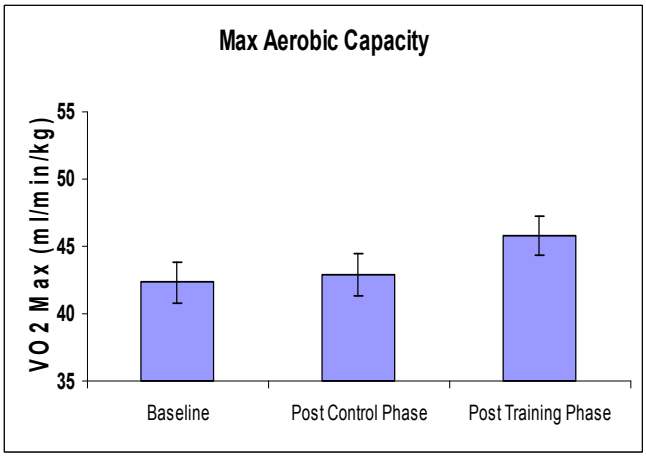

Figure 4. Average (±SE) maximal aerobic capacity ($V'O_2$ max) at baseline, and post control and training phases.

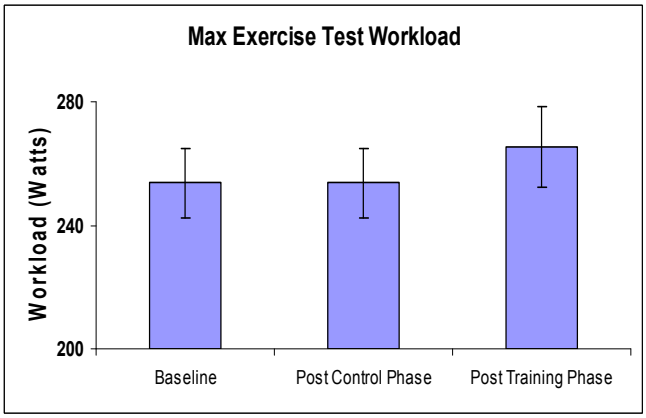

Figure 5. Average (±SE) maximal exercise test workload at baseline, and post control and training phases

IV. DISCUSSION.

The principal finding of this investigation was that a programme of repeated exposure to low frequency NMES targeting the large leg muscle groups resulted in significant improvements in aerobic fitness in a group of healthy physically active adult subjects.

Our subjects demonstrated a baseline level of aerobic fitness, having an average $V'O_2$ max of 43.7±6.5 ml/kg/min (MALE) and 38.3±5.3 ml/kg/min (FEMALE). This corresponds to a level of aerobic fitness that is considered 'good' with respect to the general population [9] and indicates a relatively high level of baseline fitness. To our knowledge, this is the first time that such a training effect is observed in a physically active population using NMES as an exercise training modality. The present results suggest that this form of NMES has considerable potential as an alternative means of promoting a training response in a physically active population.

We did not measure $V'O_2$ or heart rate during the training sessions. However, we have done this in previous work in which have demonstrated that this form of low frequency NMES was well tolerated by a healthy population and

subjects could effectively exercise at moderate intensities, as measured using the Borg RPE subjective rating scale, HR and $V'O_2$ [7]. Based on this work, and the subjective feedback received from subjects, we can estimate that the subjects in the present study were training at a conditioning intensity of approximately 50% of their $V'O_2$ max. Our results demonstrate that this modest conditioning intensity produced an average aerobic capacity improvement of 7%. This is less than the level of improvement (approx 10%) that we have observed in other populations (sedentary adults and patients with heart failure) who underwent a similar training programme [5] [6]. The difference can be explained by the fact that individuals who have a higher level of baseline fitness usually experience a lower proportional response to a given training stimulus that those starting at a lower baseline [9]. Given the fact that the subjects in this investigation had a relatively high level of baseline fitness, the observed average increase of 7% is quite respectable. Furthermore, 17 of the 18 subjects demonstrated a positive training effect, however modest. The only subject who did not show an improvement demonstrated a very small decrease (<2%) in $V'O_2$ max. Of those who did improve, 10 demonstrated an improvement of over 5%.

The training was well tolerated by subjects and we had full compliance with the programme as prescribed. Subjectively, subjects reported that the NMES was moderately uncomfortable yet did not feel that the level of discomfort experienced was disproportionate to the intensity of exercise. However, the majority of subjects also report that they would prefer to undertake voluntary means of physical activity such as jogging instead of using low frequency NMES as a long term training modality. This suggests that it may be most useful as an alternative means of training in situations where voluntary training is not advisable. As such, it could provide an alternative exercise modality during sports injury rehabilitation when patients need to perform cardiovascular exercise in a safe manner without loading the limbs or joints. It may also offer a viable means of introducing an element of variety to training efforts for those individuals who undertake large training volumes and are susceptible to issues relating to boredom, staleness, overtraining and overuse injury. Finally, we believe that this form of NMES may be of value in maintaining fitness levels in a microgravity environment as it offers a means of loading the cardiovascular system without the need to interact with external mechanical apparatus.

The low frequency NMES approach utilized in the present study offers a means of increasing oxygen demand with repetitive short duration isometric co-contractions of large leg muscle groups. Previous efforts to cause such an increase in oxygen demand using longer duration isometric exercise (with higher frequency currents) have produced responses consistent with a doubling of resting metabolic energy expenditure [10], an exercise intensity that would not be sufficient to elicit a training response in even a sedentary population.

The results of the present investigation are very encouraging. However, there is a requirement for more research to optimize the low frequency NMES approach to cardiovascular exercise training and to ascertain its range of physiological effects.

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Research article

Effects of a Whole-Body Electrostimulation Program on Strength, Sprinting, Jumping, and Kicking Capacity in Elite Soccer Players

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Abstract

The aim of the present study was to investigate the effect of a 14-week dynamic Whole-Body Electrostimulation (WB-EMS) training program on muscular strength, soccer relevant sprint, jump and kicking velocity performance in elite soccer players during competitive season. Twenty-two field-players were assigned to 2 groups: WB-EMS group (EG, n = 12), jump-training group (TG, n = 10). The training programs were conducted twice a week concurrent to 6-7 soccer training sessions during the 2nd half of the season. Participants were tested before (baseline), during (wk-7) and after (wk-14). Blood serum samples for analyzing IGF-1 and CK were taken before each testing, 15-30min post and 24h post the training program. Our findings of the present study were that a 14-week in-season WB-EMS program significant increased one-leg maximal strength (1RM) at the leg press machine (1.99 vs. 1.66 kg/kg, p = 0.001), and improved linear sprinting (5m: 1.01 vs. 1.04s, p=0.039), sprinting with direction changes (3.07 vs. 3.25s, p = 0.024), and vertical jumping performance (SJ: 38.8 vs. 35.9cm p = 0.021) as well as kicking velocity (1step: 93.8 vs. 83.9 km·h^{-1}, p < 0.001). The TG showed no changes in strength and performance. The EG revealed significantly increased CK levels 24h post training and yielded significantly higher CK levels compared to the TG. IGF-1 serum levels neither changed in the EG nor in the TG. The results give first hints that two sessions of a dynamic WB-EMS training in addition to 6-7 soccer sessions per week can be effective for significantly enhancing soccer relevant performance capacities in professional players during competitive season.

Key words: EMS, whole-body, strength training, direction changes, elite athletes, football

Introduction

The physical demands of soccer players changed over the last 10 years due to modern game philosophies and tactics. Especially, the distances covered in the higher intensities and the number of explosive actions such as accelerations, turns, and jumps have increased (Di Salvo et al., 2010; Mohr et al., 2003). Therefore, a player´s sprint ability and the dynamic and explosiveness of his movements are some of the most crucial criteria in today's talent scouting.

The results of our previous meta-analysis of EMS methods reveal that EMS training can be an effective alternative to the traditional resistance training and/or power training for developing maximal strength, speed strength, sprinting and jumping performance in elite athletes (Filipovic et al., 2012). Several studies with elite athletes revealed positive effects of EMS on performance (Babault et al., 2007; Billot et al., 2010; Brocherie et al., 2005; Maffiuletti et al., 2000; 2002; Pichon et al., 1995; Willoughby and Simpson, 1996). Despite an already high level of strength of elite athletes, several studies were able to verify high gains of >30% in the maximal strength of the lower body muscles (Babault et al., 2007; Kots and Chwilon, 1971; Willoughby and Simpson, 1996; 1998). Some studies were able to directly transfer the strength gain into an improved vertical jumping (Babault et al., 2007; Herrero et al., 2006; Kots and Chwilon, 1971; Maffiuletti et al., 2000; 2002; Pichon et al., 1995) and sprinting performance of up to -4,8% (Herrero et al., 2006; Kots and Chwilon, 1971) within 3-6 weeks (cf. Ferrando et al., 1998; Filipovic et al., 2012). Other studies showed no effects on sprinting performance (Babault et al., 2007; Billot et al., 2010). Previous investigations revealed that the combination of EMS training with specific jump training (Herrero et al., 2006; Martinez-Lopez et al., 2012; Maffiuletti et al., 2002) or high-performance training have positive effects on the strength transfer and thus enhancing motor abilities such as jumping or sprinting performance in elite athletes (Babault et al., 2007; Maffiuletti et al., 2000; Malatesta et al., 2003; Pichon et al., 1995).

All of these studies applied EMS only to defined muscles of the lower body with single electrodes. With the new generation of EMS-devices several muscle groups can be trained simultaneously through an electrode belt- and vest system (e.g., miha bodytec, Augsburg, Germany). In comparison to the local EMS method (see above) there is only little research about applying WB-EMS methods with trained athletes (Kreuzer et al., 2006; Speicher et al., 2009) and almost no data about implementing WB-EMS in the training routine of elite team athletes for systematically enhancing sport performance.

The documentation of the CK-level is a widely used parameter in high-performance sports to control training intensity and recovery. Intense physical exercise stresses muscle tissue, which elevates the level of the CK in the blood serum. Accordingly, the serum CK-level is used as an indicator for muscle damage. Extreme muscle stress and subsequent damage or several intense stimuli on consecutive days can cause a summation of CK values. In contrast to voluntary exercise, EMS artificially activates muscle contraction without resistance load. Studies investigating the stimulation intensity and the responds of creatine kinase to EMS have shown that the electrical stimulus can produce higher muscular stress and conse-

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quently a higher degree of muscle fiber damage than voluntary stimulus (Boeckh-Behrens et al., 2006; Jubeau et al., 2008; Kreuzer et al., 2006; Steinacker, 1999). Jubeau et al. (2008) assume that this could be due to the different recruitment of motor units during EMS compared with voluntary contractions.

Although little is known about the underlying mechanisms, some authors speculate neural adaptations such as a preferential activation of the large motor units of the type-II fibers with EMS as the main factor for the increase in strength (Hortobagyi et al., 1999; Maffiuletti et al., 2000; 2002; Pichon et al., 1995; Willoughby and Simpson, 1996). Hortobagyi and Maffiuletti (2011) concluded that EMS-programs up to six weeks may induce alterations in muscle metabolism. However, the authors stated that the increase in MVC (maximum voluntary contraction) is not a result of overt muscle hypertrophy and more due changes in some elements of the nervous system. Studies which applied EMS for time periods longer than six weeks suggested that hypertrophy might occur in the late phase of such programs (cf. Hortobagyi and Maffiuletti, 2011; Gondin et al., 2005, 2011; Ruther et al., 1995). Anabolic hormones such as the human growth hormone (hgH) play a dominant role in the regulation of protein metabolism and can be an indicator for muscle growth and hypertrophy. Jubeau et al. (2008) investigated the acute effect of EMS on hgH. They observed a significant increase in hgH for the EMS-group compared to traditional strength training. However, the authors did not investigate the changes in muscle mass. IGF-1 is also an anabolic hormone that is part of a signaling network that is involved in exercise-induced remodeling processes in the muscle (Goldspink, 2005; Hameed et al., 2003). In adaptation to resistance training IGF-1 increases the protein synthesis in the muscle cells (Butterfield et al., 1997; Ferrando et al., 1998). Further, IGF-1 activates satellite cells to proliferate and differentiate and thus could modulate skeletal muscles (Adams and Haddad, 1996). Resistance exercise is a powerful stimulus for the endocrine system. Studies have shown that the hormonal response to resistance exercise depend on several factors including number of sets, repetitions, training intensity and volume and rest intervals (Crewther et al., 2006). Research studies dealing with the acute response to IGF-1 have shown that strength exercise can elevate circulating IGF-1 and free IGF-1 (Kraemer and Ratamess, 2005; Rahimi et al., 2010). In contrast, other studies have shown no changes in acute IGF-1 after resistance exercise (Kraemer and Ratamess, 2005). No studies have yet investigated the acute metabolic responses to WB-EMS in elite athletes.

To our knowledge this is the first field-practice study that systematically implements a WB-EMS program in training routine of elite soccer players over 14 weeks to increase performance and test the WB-EMS method on practicability in professional soccer. Little is known about the underlying mechanisms of EMS, e.g. no studies have yet investigated the acute metabolic responses to WB-EMS in elite athletes.

For these reasons the aim of this study was to implement a dynamic whole-body EMS program in the in-season training routine of elite soccer players on the basis of our previous studies to investigate the effects on maximal strength, sprinting and jumping performance, and kicking capacity. A further objective of this study was to investigate the effects on hormonal (insulin-like-growth-factor-1) and enzymatic (creatine kinase) parameters in order to explain possible adaptation mechanisms such as hypertrophy.

Methods

Participants

Twenty-two professional male soccer players, competing in the 4th division of the German Soccer Federation (DFB), voluntarily participated in this study. To our knowledge this is the first study to implement WB-EMS in the training routine of elite soccer players. In accordance with the principles of players´ preference intervention, only players who did not have a strong group preference were randomized into either the WB-EMS group (EG) or the Jump-Training group (TG). To cope with possible dropouts in the WB-EMS group the players were assigned into a larger intervention group (EG) and a smaller control-group (TG): WB-EMS group (EG, n = 12; age 24.9 ± 3.6 years; height 1.84 ± 0.05 m; mass 80.6 ± 9.2 kg), control-group (TG, n = 10; age 26.4 ± 3.2 years; height 1.82 ± 0.07 m; mass 78.3 ± 9.3 kg). All players were professional soccer players and performed 6-7 training sessions per week and competed once a week in the championships. The standard training sessions lasting 70-90min including technical skill activities, offensive and defensive tactics, athletic components with various intensities, small sided game plays and 20-30min of continuous play. The playtime in championship- or friendly matches of the test persons were recorded during the study period (Table 1). The players were asked to maintain their usual food intake und hydration. During the study no additional strength training for the lower body was allowed. The study was conducted in the second half of the season from January until May. All players had at least five years of experience in systematic strength training. During the first half of the season strength training sessions were part of their daily soccer training routine minimum once a week. None of the players had trained with EMS before. All players were informed about the procedures and risks of the study and written informed consent was obtained. All experimental procedures performed were approved by the Ethic Committee of Human Research of the German Sport University Cologne.

Table 1. Playtime (minutes) in EMS-Group (EG) and Jump-Training-Group (TG) during the 14-week investigation period. Playtime was documented from week 0 until week 7 (Baseline - wk-6) and from week 7 until posttest in week 14 (wk-7 – wk-14). Values are presented in means (±SD).

	wk0-wk6	wk7-wk14
EG	561.9 (170.2)	879.3 (701.4)
TG	623.9 (115.1)	640.0 (610.6)

Experimental design

The study was designed as a randomized training study including a jump training group with simultaneous EMS

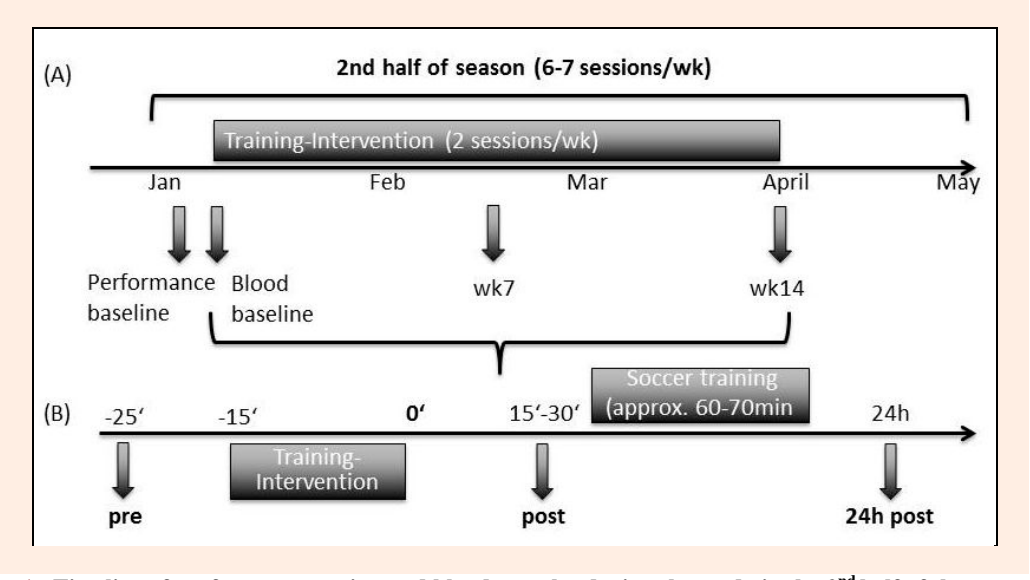

Figure 1. Timeline of performance testing and blood samples during the study in the 2nd half of the season (A). Timeline of blood samples collection at baseline, wk 7, and wk 14. At each testing samples were taken before (pre), after 15-30min (post), and 24h (24h post) after the training interventions (B).

(EG) and a jump training group without EMS (TG) as control group in order to investigate the effects of the WB-EMS stimulus on maximal strength and performance and exclude the possible effects of the squat jumps. The study was conducted during the second half of the competitive season. The training interventions were conducted twice per week in addition to 6-7 soccer training sessions and a match on the weekend. Performance was assessed before (baseline) after 7 weeks (wk7), and after 14 weeks (wk14) (Figure 1). All performance diagnostic tests were performed on Tuesday mornings in a standardized order as listed below. The 10 min standardized warm-up included dynamic movement preparations and static stretching. At the end of each warm-up followed by short movement activation phase the players performed three increased runs over 30m and three all-out sprints over 10m. No static stretching was allowed after warm-ups. The sprint tests and kicking tests were performed on an artificial ground (*POLYTAN*, FIFA norm 1 star). Vertical jump tests and strength tests were performed indoor in the club gym.

Testing procedures

Anthropometric parameters

Before each testing we documented the players´ age (years), body height (cm), body weight (kg) (Table 1).

Linear sprint and sprint with direction changes

First, the players performed three linear sprints over 30m and then four soccer relevant sprints with direction changes over 15m according to Rehhagel (2011). The sprints with direction changes included a 1m sidestep after start, followed by a 10m linear sprint and a 5m sprint after a direction change of 45 degrees. To standardize the direction change the players had to hit two marks on the ground, one with each foot. The players performed two sprints from each side. Between the sprints the players rested for 120 s. Sprint time was measured with double infrared photoelectric barriers with radio transmitter (DLS/F03, Sportronic, Leutenbach-Nellmersbach, Germany) positioned 1m from the ground. The players started the sprints from a standing position - 50cm for linear and 10cm for sprint with direction changes - behind the first photoelectric barrier. The fastest of the three respectively four trials was used for statistical analysis.

Kicking velocity

The players performed three shots from a distance of 6m with no run up (one step before kicking) and three shots with run up (3 steps before kicking) into a 100x80cm soccer goal by using the dominant leg (cf. Billot et al., 2010). An official FIFA match soccer ball (size 5, 440g) by JAKO with a pressure of 11.5psi was used (cf. Billot et al., 2010). Pressure was checked before each testing session. Ball speed was measured with "Speed TracX Sportradar" (10,525GHz). The radar device was positioned 40cm from the ground directly behind the net of the soccer goal. The fastest out of three trials was used for statistical analysis.

Vertical jump

The vertical jump height was measured with an "OptoJump" (Microgate, Bozen, Italy). The "OptoJump" device measures the jump height by measuring the flight time with the help of infrared photoelectric barriers. The players performed three trials of each vertical jump variation including one test jump. First, the players performed three vertical jumps starting from a static squatted position with knees 90 degrees (SJ) without any preliminary movement. For countermovement jump (CMJ) the players started from a standing position squatting down to a knee angle of approximately 90 degrees in order to build up momentum and then explosively jump as high as possible. The highest jump of the 3 trials per jump type was used for analysis. The drop jump (DJ) was performed from a box (38cm). Therefore, the players stepped respectively

jumped down from the box and then tried to jump as high as possible. The players were told to aim a contact time on the ground below 200ms. The players were instructed to keep their hands on the hips throughout all jump tasks. The highest relation (DJindex) between jump height and shortest contact time out of the three trials (jump height [cm]*10/contact time [ms]) was used for statistical analysis.

Maximal muscular strength

Tests were performed on a leg press machine (NORSK, Sequenztraining-system, Cologne, Germany). The players were positioned horizontal on the sledge with the hip and knee angle under 90°. The maximal strength of each leg was measured by the one-repetition-maximum (1RM) according to Beachle (1994). The players performed two series with 10 dynamic repetitions with submaximal weight for warm-up. To determine the 1RM, the players were allowed to use both legs to get in starting position with legs fully extended (180°). For testing, the players performed maximal repetitions with one leg (ROM knee angle 180°-90°, 2s/2s). If a player mastered more than six repetitions, a load of 10kg was added to the sledge for the next set after allowing a recovery interval of about three min.

Bloodparameters - CK and IGF-1

In each testing (baseline, wk7, wk14) blood samples were withdrawn before (pre), 15-30min after (post) and 24h after the interventions (24h post) (Figure 1). The players were told to maintain a seated position after the interventions for 15 min till the first blood samples were collected. Blood samples were stored – 80°C and were analysed after completing the study. Creatine kinase (CK) and the IGF-1 were analysed by Enzyme-linked Immunosorbent Assay (ELISA)-method according to the manufacture instructions (R&D Systems, Minneapolis, USA). All blood samples were taken on Thursdays (pre and post) between 10:00h and 12:00h before the soccer training session and on Fridays at the same time (24h post). The players´ nutrition on the test days was recorded and the players were instructed to maintain the usual nutrition. No nutrition supplements were allowed during the study period.

Experimental training protocol

WB-EMS training was conducted on Mondays and Thursdays in order to obtain a rest interval of 48 hours between the two sessions and the championship game on Saturdays. The WB-EMS Training was conducted with a whole body-EMS-system by "*miha bodytec*" (Augsburg, Germany). WB-EMS was applied with an electrode vest to the upper body including the chest (m. pectoralis major and minor), upper back and lower back (m. latissimus, m. trapezius, m. erector spinae, m. iliolumbales), and abdominals (m. rectus abdominis) and with a belt system to the lower body including the muscles of the glutes (m.gluteus maximus and medius), thighs and hamstrings (m. rectus femoris, m. vastus medialis and lateralis, m. biceps femoris, m. semitendinosus, m. semimembranosus, m. gracilis) and calves (m. gastrocnemius, m. soleus). The electrode belt for the thighs was positioned between hip and the knee joint space. For the calves, the belts were placed around the thickest part of the calves. The players started with a 2-3 min warm-up with easy movement preparations and jumps at a light to moderate stimulation intensity. The players were told to slowly increase the intensity every few impulses. The training started when the players reached the defined training intensity (see below). The EG performed 3x10 maximal squat jumps with a set pause of 60s (no currents) per session. Biphasic rectangular wave pulsed currents (80Hz) were used with an impulse width of 350µs. Every impulse for a single jump lasted for 4s (ROM: 2s eccentric from standing position to an knee angle of 90° – 1s isometric – 0.1s explosive concentric – 1s landing and stabilisation) followed by a rest period of 10s (duty cycle approx. 28%).

The stimulation intensity was determined and set separately for each muscle group by using a Borg-scale (6-20, [20-100%]). For the first two sessions the participants started with a moderate to sub-maximal intensity (13-15, [50-60%]). The stimulation intensity was then constantly increased individually every week. The players were told to maintain a high stimulation intensity (Borg-Scale 18-19, [80-90%]) that still assures a clean dynamic jump movement.

The TG performed the same amount of jumps with identical interval and conduction twice per week on similar days without EMS in addition to the 6-7 soccer specific training sessions per week.

All testing and training sessions were supervised and monitored by a strength and conditioning specialist.

Statistical analysis

The Kolmogorov-Smirnov test of the normality of distribution was conducted before the analysis. All parameters were normally distributed. Potential baseline differences between treatment groups were investigated using the student t-test for independent samples. Assumption of homogenous variances was tested using Levene test. In case of inhomogeneous variances Welch-test was used. To determine the effect of the training interventions a separate 3x2 (time*group) mixed ANOVAs with repeated measures were conducted. ANOVA assumption of homogenous variances was tested using Maulchy-test of Sphericity. If a violation of Mauchly´s test was observed Greenhouse-Geisser correction was used. Partial eta-square (η^2_p) values are reported as effect size estimates. If 3x2 mixed ANOVA revealed a significant time-point*treatment or time*group interaction effect on any variable, this effect was further investigated carrying out Bonferroni corrected post hoc pairwise comparison. To detect correlations among pairs of variables Pearson product-moment correlation (one-tailed) was used. For all inferential statistical analyses, significance was defined as p-value less than 0.05. All descriptive and inferential statistical analyses were conducted using SPSS 22® (IBM®, Armonk, NY, USA).

Results

Effects on performance parameters

Group Comparisons: At the baseline test the TG showed a significant ($p < 0.05$) lower sprint time for linear sprint over 10m, and a higher kicking velocity with 1step run-up than the EG. After 14 weeks, the EG showed a significant ($p < 0.05$) higher 1RM at the leg press than the TG at wk7 ($p < 0.05$) and at wk14 ($p < 0.05$).

Anthropometric changes: We observed no changes in body weight and height in both groups during the study period.

One-Repetition-Maximum (1RM) legpress machine: The 3x2 mixed ANOVA on 1RM revealed a significant main effect of within-subjects factor time ($F = 9.481$, $d = 16$, $p = .002$, $\eta^2_p = 0.542$), and a significant time*group effect ($F = 8.169$, $d = 16$, $p = 0.004$, $\eta^2_p = 0.505$). Significant interaction effect on relative 1RM was further analyzed through post hoc comparisons. We observed significant increases for the EMS group (EG) in the maximal strength (1RM) at wk7 ($p < 0.01$) and wk14 ($p < 0.01$) compared to the baseline. The TG showed no changes in the maximal strength (Figure 2).

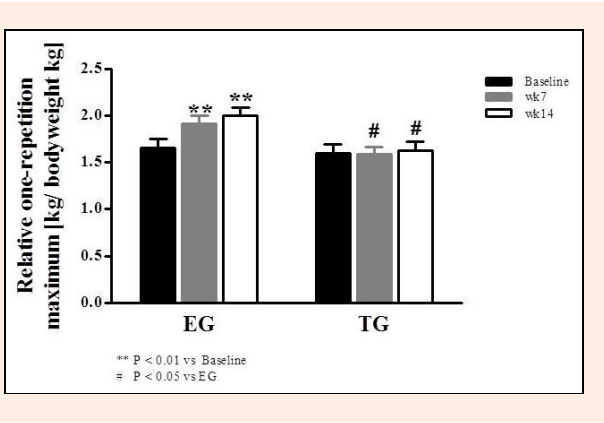

Figure 2. Relative maximal strength (1RM) at the leg press machine (one-legged) in EMS-Group (EG) and Jump-Training-Group (TG) measured before (baseline) after wk 7, and after wk 14. Values are presented in means ± SD, and significant differences at $p < 0.05$ (*) and $p < 0.01$(**).

Vertical jump: We observed a significant main effect of within-subjects factor time for SJ ($F = 11.268$, $d = 17$, $p = 0.001$, $\eta^2_p = 0.57$), CMJ ($F = 9.625$, $d = 17$, $p = 0.002$, $\eta^2_p = 0.531$), DJindex ($F = 10.427$, $d = 17$, $p = 0.001$, $\eta^2_p = 0.551$) and a significant time*group effect for squat jump ($F = 6.104$, $d = 17$, $p = 0.01$, $\eta^2_p = 0.418$). The EG showed significant increases in SJ ($p < 0.05$), CMJ ($p < 0.05$) and DJindex ($p < 0.01$) at wk14 ($p < 0.05$). The TG showed no significant changes in SJ, CMJ, and DJindex compared to baseline (Figure 3).

Linear sprint: Concerning sprint performance we documented a significant time*group effect only for 5m ($F = 3.962$, $d = 17$ $p = 0.039$, $\eta^2_p = 0.318$). For 10m the analysis showed a non-significant time*group effect ($F = 3.52$, $d = 17$, $p = 0.53$, $\eta^2_p = 0.293$). We observed an improvement in the short sprint time for EG only over 5m ($p < 0.05$). The 10m sprint times improved till wk7 but remained insignificant ($p = 0.53$) compared to baseline. The 20m, and 30m sprint times remained unchanged during the study. The linear sprint times for TG showed no significant changes in all measuring points for the entire study period (Figure 4).

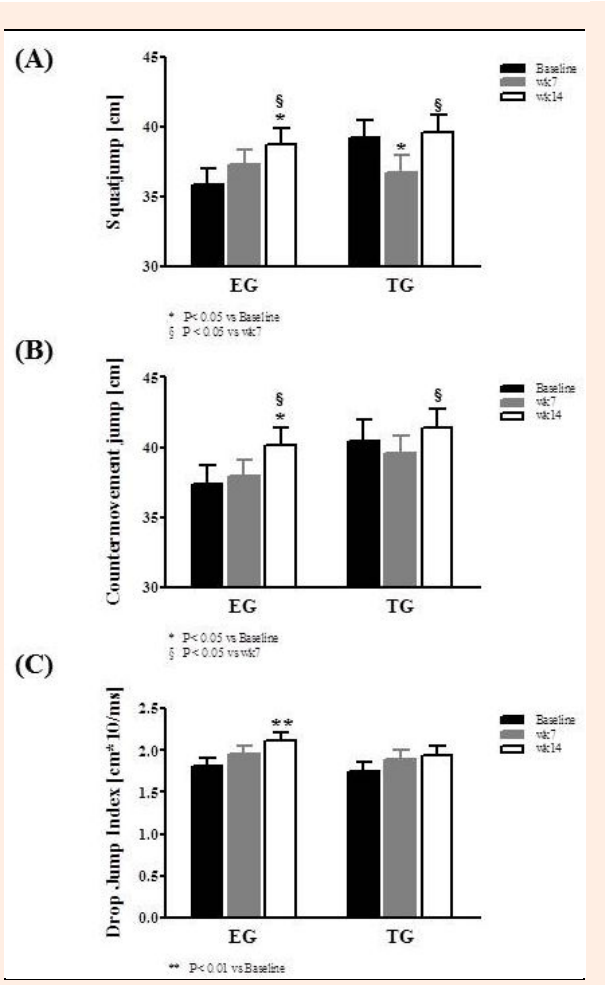

Figure 3. Squat Jump (A), Counter-Movement-Jump (B), and Drop Jump Index (C) in EMS-Group (EG) and Jump-Training-Group (TG) measured before (baseline) after wk 7 and after wk 14. Values are presented in means ± SD, and significant differences at $p<0.05$ (*) and $p<0.01$(**).

Sprint with direction changes: We showed a significant main effect of within-subjects factor time ($F = 6.169$, $d = 16$, $p = 0.01$, $\eta^2_p = 0.435$). The post-hoc analysis showed an improvement for EG at wk7 ($p < 0.05$), and wk14 ($p < 0.05$) compared to baseline. Sprint performance remained unchanged for TG (Figure 5).

Kicking capacity: The ANOVA revealed for both kicking variations significant main effects of within-subjects factor time (1-step: $F = 15.212$, $d = 15$, $p < 0.001$, $\eta^2_p = 0.67$; 3-step: $F = 5.378$, $d = 15$, $p = 0.017$, $\eta^2_p = 0.67$), and a significant time*group effect for 1-step ($F = 5.378$, $p = 0.017$, $\eta^2_p = 0.418$). For kicking performance, we observed for the EG a significant increase in ball speed with 1 step and 3 steps run-up at wk14 (1step, $p < 0.01$; 3step, $p < 0.05$. We observed no change in kicking performance for TG (Figure 6).

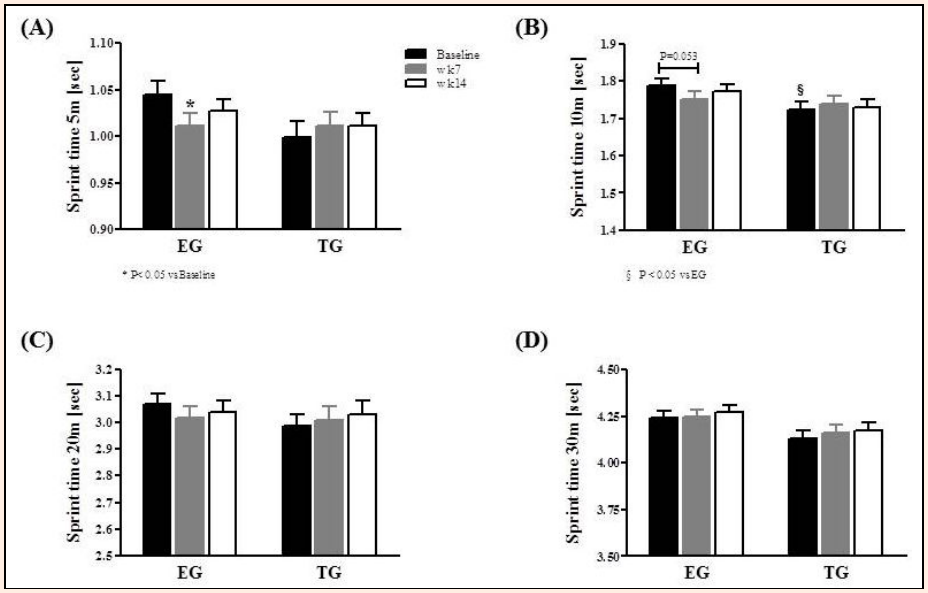

Figure 4. Linear Sprint performance at 5m (A), 10m (B), 20m (C), and at 30m (D) in EMS-Group (EG) and Jump-Training-Group (TG) measured before (baseline) after wk 7, after wk 14. Values are presented in means ± SD, and significant differences at p < 0.05 (*).

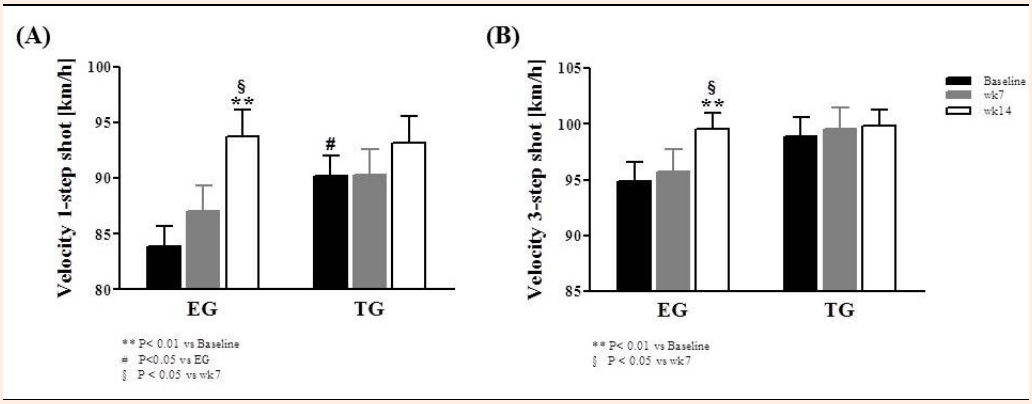

Figure 6. Kicking velocity (Ball speed km·h^{-1}) ith 1 step run-up (A) and 3 steps run-up (B) in EMS-Group (EG) and Jump-Training-Group (TG) measured before (baseline) after wk 7 and after wk 14. Values are presented in means ± SD, and significant differences at p<0.05 (*) and p<0.01 (**).

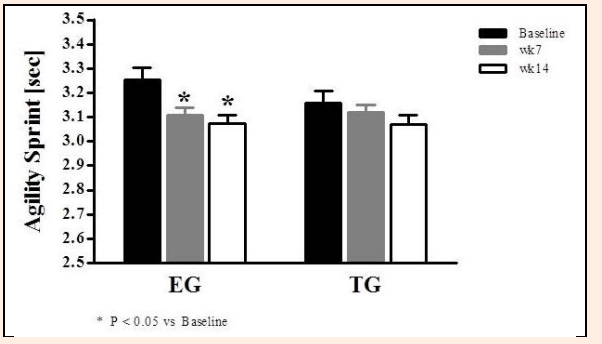

Figure 5. Sprint performance with direction changes over 15m in EMS-Group (EG) and Jump-Training-Group (TG) measured before (baseline) after wk 7 and after wk 14. Values are presented in means ± SD, and significant differences at p < 0.05 (*).

Correlations: At wk7 we documented a significant correlation between the gains (wk7-baseline) in leg press 1RM and the improvement in SJ performance (r = 0.422, p = 0.047) and linear sprint at 5m (r = -0.470, p = 0.021). Further, the analysis showed significant correlations between improvements in SJ and CMJ (r = 0.526, p = 0.009), linear sprint at (5m: r = -0.601, p = 0.003; 10m: r = -0.497, p = 0.013) and sprinting with direction changes over 15m (r = -0.397, p = 0.042). For CMJ the analysis showed significant correlation for sprinting with direction changes (r = -0.602, p = 0.003) and kicking velocity (1step: r = 0,402, p = 0.049; 3step: r = 0.556, p = 0.008). At wk14 we documented a significant correlation between the gains (wk14-baseline) in leg press 1RM and the improvement in CMJ performance (r = 0.475, p = 0.02). Correlations for squat jump were significant with gains in SJ performance (r = 0.671,p = 0.001) and kicking velocity (1step: r = 0.558, p = 0.008; 3step: r = 0.510, p = 0.015). For countermovement jump the analysis showed significant correlation between gains in CMJ performance and

sprinting with direction changes (r = -0.400, p = 0.045) and kicking velocity (1step: r = 0.497, p = 0.018; 3step: r = 0.481, p = 0.022). Further, we documented correlations between the gains in DJindex and the improvements in linear short sprint (5m: r = -0.78, p < 0.001; 10m: r = -0.61, p = 0.002), and kicking velocity (1step: r = 0.43, p = 0.01; 3step: r = 0.448, p = 0.31). We documented no significant correlations between the gains of the other parameters.

Effects on blood parameters

Creatine kinase (CK): Concerning the long-term effects, we observed a non-significant main effects for factor time ($F = 3.692$, $d = 11$, $p = 0.056$, $\eta^2_p = 0.402$), and a significant time*group effect ($F = 4.967$, $p = 0.029$, $\eta^2_p = 0.475$). The post-hoc analysis showed a significant increase of CK for EG only at wk7 ($p < 0.05$) compared to baseline. Regarding the acute effects, we observed a significant increase of CK from pre to 24h post for EG in the first session at baseline ($p < 0.01$) and in the tests at wk7 ($p < 0.05$). There was no significant acute increase at wk14. In the TG, CK remained unchanged to baseline till wk14. No differences were observed between pre to 24h post values in all tests.

For group comparison, the EG showed a significant higher pre CK value ($p < 0.05$) and 24h post value ($p < 0.01$) compared to the TG at wk7. There were no significant differences in the pre and 24h post CK values at baseline and wk14 (Figure 7).

Insulin-like growth factor-1 (IGF-1): Regarding the IGF-1 we observed no significant main effect for time and time*group. Both groups showed no significant changes in the pre IGF-1 values from baseline to wk14. Regarding the acute effects the analysis showed no changes from pre to 15-30min post and 24h post intervention for EG and TG. There was no significant group difference between the groups in all tests.

Discussion

The main findings of this study were that two WB-EMS sessions in addition to 6-7 soccer training sessions per week over 7-14 weeks (14-28 sessions) can be sufficient to enhance physical performance such as leg press 1RM, jumping and sprinting performance, and kicking capacity in professional soccer players. However, jumping and kicking performance showed delayed adaptations and were not significant after 7 weeks. Regarding strength adaptations, we observed no effect on IGF-1 and no changes in body weight that both could have indicated a hypertrophy effect. In contrast to the TG CK values were strongly increased after WB-EMS sessions.

Effects on strength and performance

In regards to maximal strength (1RM) the professional soccer players in this study showed significant increases in leg strength (1RM) of +16.83 ± 13.06% after 7 weeks (14 sessions) and +22.42 ± 12.79% after 14 weeks (28 sessions) of dynamic WB-EMS. These gains in maximal strength (1RM) have not been shown by studies using WB-EMS yet (Boeckh-Behrens and Treu, 2002; Boeckh-Behrens and Mainka, 2006; Kreuzer et al., 2006; Speicher and Kleinöder, 2009). Considering maximal strength and jumping performance our results are in line with the findings of studies using local EMS-training (12-28 sessions) on the lower body muscles in trained and elite athletes (Babault et al., 2007; Filipovic et al., 2012; Kots and Chwilon, 1971; Maffiuletti et al., 2000; 2002; Willoughby and Simpson, 1998). Regarding the parameters of speed strength and power, the studies by Kreuzer et al. (2006) and Speicher et al. (2009) using isometric and dynamic WB-EMS achieved only low gains in maximal strength but remarkable gains in rate of force development and force impulse after four weeks (8 sessions), but couldn´t transfer the gains into jumping performance. One reason for this could be the difference between training movement and test movement (e.g. isometric vs. dynamic), which can hamper the transfer. A further reason could be the relatively short study duration of four weeks and the lower number of training sessions. Compared to this study (8 vs. 14 sessions) strength parameters might need more than 8 sessions respectively longer time to develop.

In this study strength gains in the EG could directly transfer to the players´ performance and result in a

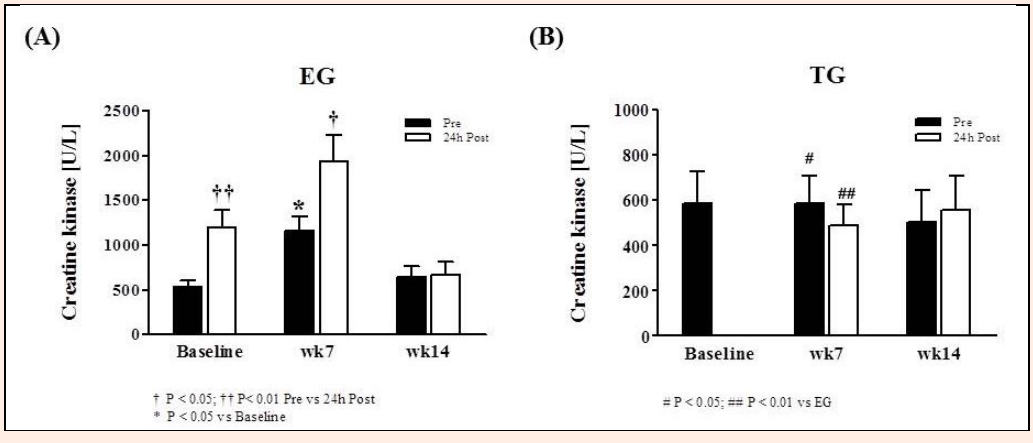

Figure 7. Creatine kinase (CK) levels in the (A) EMS-Group (EG) and (B) Jump-Training-Group (TG) at baseline, wk 7 and wk 14. CK was measured in the blood serum before (pre) and 24h after (24h post) the training interventions. Values are presented in means ± SD, and significant differences at p<0.05 (*) and p<0.01 (**).

significant improvement of jumping, sprinting, and kicking performance. According to this, we documented a significant correlation between the gains in leg press 1RM and the improvement in squat jump performance ($r = 0.422$, $p = 0.047$) and linear sprint at 5m ($r = -0.470$, $p = 0.021$) in wk7 (wk7-baseline). Further, the analysis showed significant correlations between improvements in squat jump and linear sprint at 5m ($r = -0.601$, $p = 0.003$), at 10m ($r = -0.497$, $p = 0.013$) and sprint with direction changes over 15m ($r = -0.397$, $p = 0.042$). In comparison to the EG, the maximal strength (1RM) in leg press remained unaltered in the TG during the study. That argues for the stagnation in jumping and sprinting performance. Furthermore, these results suggest that on a high-performance level 30 maximal squat jumps twice a week, as applied in this study (work/rest: 4s/10s), are not sufficient to enhance leg strength or jumping performance in elite soccer players.

Studies have shown that the strength of the m. quadriceps femoris and especially the reactive ability of the m. triceps surae influence jumping and sprinting performance (Weineck, 2007; Wissloff, 2004). Considering reactive strength ability, we documented correlations between the gains in DJindex (wk14-baseline) and the improvements in linear short sprint (5m: $r = -0.78$, $p < 0.001$; 10m: $r = -0.61$, $p = 0.002$), and kicking velocity (1step: $r=0.43$, $p = 0.01$; 3step: $r = 0.448$, $p = 0.31$), and a trend in sprinting with direction changes ($r = -0.379$, $p = 0.055$) from baseline to wk14 (wk14-baseline). Accordingly, the stimulation of the calve muscles in addition to the thigh muscles, seem to have a positive effect on the reactive strength ability and thus on drop jump and sprint performance (linear and multidirectional). Our findings support the results from previous EMS-studies that showed positive effect of the additional stimulation of the m. triceps surae on performance (cf. Filipovic et al., 2012). For example, Maffiuletti et al. (2002) stimulated the m. quadriceps femoris and the m. triceps surae of professional volleyball players over four weeks (12 sessions) in combination with a plyometric jump training. The authors documented significant increases in maximal strength in both muscle groups of >25% and showed increases of >20% in SJ performance and >10% in DJ performance. In comparison, after 7 weeks (14 sessions) we documented increases of +16.83 ± 13.06% in 1RM leg press, +4.23 ± 7.71% in SJ, +9.98 ± 20.96% in DJindex, -1.77 ± 2.34% in 10m linear sprint, and -4.92 ± 3.76% in sprint with direction changes.

However, this study design does not allow to conclude that WB-EMS alone is sufficient to increase maximal strength and soccer relevant performance parameters.

Possible adaptation mechanisms

In regards to the strength adaptations we documented no changes in body weight after 14 weeks of EMS training. Furthermore, the WB-EMS showed no acute or long-term effects on IGF-1. Growth factors such as IGF-1 or hgH play an important role during tissue remodeling (cf. Kraemer and Ratamess 2005) and can be indicators for a hypertrophy effect. Jubeau et al. (2008) investigated the acute effect of EMS on human growth hormone (hgH). They observed a significant greater increase in hgH and creatine kinase activity for the EMS-group compared to voluntary exercise. Gondin et al. (2011) applied EMS to the m. quadriceps femoris of trained athletes three times a week in addition to the usual sport specific training (4-6 hours a week). The authors observed a significant hypertrophy effect of 12% in type-I and 23% in type-II fibers together with an increase in cross sectional area of the m. quadriceps femoris after 8 weeks. The total time under tension in this study was 12.5 minutes per week (40 contractions per session, 6.25s on/20s off). In contrast, in the present study the time under tension was two minutes per session (30 contractions, 4s on/10s off) and only four minutes per week total. The lower time under tension and or the lower number of sessions per week might not be sufficient to affect growth factors such as IGF-1 and subsequently activate hypertrophy mechanisms. According to the results of this study, two WB-EMS training session per week in addition to 6-7 soccer sessions seem to have no effect on hypertrophy in elite soccer players.

Strength transfer

In the present study strength gains in one-legged 1RM at the leg press machine could directly be transferred to an improved performance in linear sprinting and sprinting with direction changes within 7 weeks (14 sessions). However, jumping and kicking velocity showed delayed adaptations and were not significant before wk14 (28 sessions). The findings reveal that strength gains achieved with WB-EMS might need a longer adaptation period (>7 weeks) when applied twice a week or a higher number of EMS-sessions per week or longer time under tension per session respectively to transfer into jumping and kicking performance within 7 weeks. Further, an highly increased stress load through EMS training in addition to the normal training/game load might negatively influence or hamper strength transfer. An additional specific plyometric training could have positively influenced the strength transfer into explosive movements such as jumping and kicking.

Compared to previous studies we only conducted two EMS sessions per week (vs. 3-4 sessions) and thus had a lower total time under tension per week (4 vs. 5-8 min) (Herrero et al., 2006; Maffiuletti et al., 2000; 2002; Babault et al., 2007; Billot et al., 2010; Malatesta et al., 2003; Pichon et al., 1995). Similar to our study design, Billot et al. (2010) investigated the influence of an EMS-training (3 sessions/wk, 5.4 min time under tension/wk) in trained (semi-professional) soccer players. After five weeks (15 sessions) the authors documented a significant improvement in dynamic leg strength and in kicking velocity. In line with our findings, the players showed no changes in vertical jumping and 10m sprinting performance after 14 sessions. Taking this in account, our findings suggest that speed strength parameters such as jumping and kicking might need more than 14 sessions or a higher total time under tension per week to significantly improve within 5-7 weeks. However, to our knowledge this was the first study that implemented WB-EMS in the training routine of professional soccer players over a period of 14 weeks. We designed this study on the basis of our previous investigation (cf. Filipovic et al., 2011).

According to this, we planned to include three WB-EMS-sessions per week in addition to the usual training routine. However, due to the lack of research with elite soccer players and the high training volume and intensity we reduced the WB-EMS sessions to two sessions per week in order to prevent the players from overtraining.

Regarding the training intensity, we observed a significant ($p < 0.05$) increase in CK in the EG at baseline (pre 530.30 ± 230.00 U/l, 24h post 1199.89 ± 569.69U/l). Due to the constant increase of the stimulation intensity (e.g. thigh electrodes +31.8±39.4%) in addition to a significant higher training load during the first six weeks (season preparation) the CK in the EG remained on a very high level ($p < 0.05$) till wk7. We observed no significant increase in CK in the TG compared to baseline during the study. The summation of higher training load and WB-EMS-training during the first 7 weeks might be overloaded some players´ muscular system that might have hampered or delayed strength transfer. For comparison, we documented an average CK of 300-500U/l in a normal training week in the first half of the season with 6-7 training sessions per week. Nedelec et al. (2014) documented CK values of >700U/l after 90 minutes of game play in professional soccer players. Our findings are in line with the results by Jubeau et al. (2008) showing that EMS training can release significant higher CK compared to voluntary exercise. From wk7 till wk14 CK values dropped again to baseline pre level together with a further increase in 1RM, jumping, sprint with direction changes and kicking velocity.

Conclusion

Two dynamic whole-body EMS sessions in combination with 30 squat jumps (12 minutes) concurrently to 6-7 soccer training sessions per week and one match are sufficient for effectively enhancing maximal strength, sprinting and jumping performance, and kicking capacity in professional soccer players. Strength gains achieved with WB-EMS might need more than 7 weeks (14 sessions) to significantly influence jumping and kicking performance when only applied twice a week.

Our findings indicate that WB-EMS training, as new stimulus, can complement or modify the common training structure and thus is able to enhance the athletic performance even of highly trained athletes.

Further studies are needed to enlarge the knowledge about practical application in this field and in view of possible undelaying mechanisms such as muscle hypertrophy or muscle fiber shift. EMG-analysis may contribute to gain knowledge about EMS induced neuronal adaptations in further studies.

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Key points

- Two WB-EMS sessions concurrently to 6-7 soccer training sessions per week enhanced maximal strength in the leg press machine within 7 weeks during competitive season.
- Sprinting and jumping performance and kicking capacity were improved after 14 weeks.
- WB-EMS did not effect serum IGF-1 levels in professional soccer players.

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