BRIEF REVIEW

ELECTROMYOSTIMULATION—A SYSTEMATIC REVIEW OF THE INFLUENCE OF TRAINING REGIMENS AND STIMULATION PARAMETERS ON EFFECTIVENESS IN ELECTROMYOSTIMULATION TRAINING OF SELECTED STRENGTH PARAMETERS

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ABSTRACT

Filipovic, A, Kleinöder, H, Dörmann, U, and Mester, J. Electromyostimulation–A systematic review of the influence of training regimens and stimulation parameters on effectiveness in electromyostimulation training of selected strength parameters. *J Strength Cond Res* 25(11): 3218–3238, 2011—Our first review from our 2-part series investigated the effects of percutaneous electromyostimulation (EMS) on maximal strength, speed strength, jumping and sprinting ability, and power, revealing the effectiveness of different EMS methods for the enhancement of strength parameters. On the basis of these results, this second study systematically reviews training regimens and stimulation parameters to determine their influence on the effectiveness of strength training with EMS. Out of about 200 studies, 89 trials were selected according to predefined criteria: subject age (<35 years), subject health (unimpaired), EMS type (percutaneus stimulation), and study duration (>7 days). To evaluate these trials, we first defined appropriate categories according to the type of EMS (local or whole-body) and type of muscle contraction (isometric, dynamic, isokinetic). Unlike former reviews, this study differentiates between 3 categories of subjects based on their level of fitness (untrained subjects, trained subjects, and elite athletes) and on the types of EMS methods used (local, whole-body, combination). Special focus was on trained and elite athletes. Untrained subjects were investigated for comparison purposes. The primary purpose of this study was to point out the preconditions for producing a stimulus above the training threshold with EMS that activates strength adaptations to give guidelines for implementing EMS effectively in strength training especially in high-performance sports. As a result, the analysis reveals a significant relationship ($p < 0.05$) between a stimulation intensity of ≥50% maximum voluntary contraction (MVC; 63.2 ± 19.8%) and significant strength gains. To generate this level of MVC, it was possible to identify guidelines for effectively combining training regimens (4.4 ± 1.5 weeks, 3.2 ± 0.9 sessions per week, 17.7 ± 10.9 minutes per session, 6.0 ± 2.4 seconds per contraction with 20.3 ± 9.0% duty cycle) with relevant stimulation parameters (impulse width 306.9 ± 105.1 microseconds, impulse frequency 76.4 ± 20.9 Hz, impulse intensity 63.7 ± 15.9 mA) to optimize training for systematically developing strength abilities (maximal strength, speed strength, jumping and sprinting ability, power).

KEY WORDS strength training, electromyostimulation, review, training parameters, EMS methods, trained athletes

INTRODUCTION

Regarding the influence of electromyostimulation (EMS) methods on strength abilities, our first study revealed the effectiveness of different EMS methods for enhancing maximal strength, speed strength, jumping and sprinting ability, and power (35). Significant gains ($p < 0.05$) were shown in maximal strength (isometric *F*max +32.6 ± 17.6%; dynamic *F*max +31.6 ± 18.8%), speed strength (eccentric isokinetic *M*max +27.7 ± 8.5%; concentric isokinetic *M*max +20.5 ± 11.5%; rate of force development (RFD) +44.8 ± 27.8%; force impulse +19.2 ± 5.8%; *v*max +19 ± 0%; and power +47.8 ± 14.9%). Developing these parameters increases vertical jump height by +15.5 ± 4.9% (squat jump [SJ] 12.9 ± 7.0%, countermovement jump [CMJ] +14.5 ± 5.8%, drop jump [DJ] +9.3 ± 3.8%) and improves sprint times by as much as −2.8 ± 1.7% in trained and elite athletes.

Compared to traditional voluntary strength training, several EMS parameters have to be considered in addition to common training regimen for training control of strength training with EMS. This complexity of different combinations

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of training regimen and stimulation parameters makes it difficult to systematically implement EMS.

In voluntary strength training, the resistance of additional weight regulates the training intensity because of the maximum voluntary contraction (MVC), which is defined as 1 repetition maximum. In contrary to voluntary exercise EMS activates muscle contraction artificially without using a resistance load. For this reason, it is not possible to simply transfer conventional training regimens into strength training with EMS. Despite the difference in muscle activation, the design of most EMS studies leaned heavily on traditional strength training parameters (cf. (5,22,34,55,75,76)). Several studies showed that electrical stimulus can be more intense than voluntary stimulus activated by the central nervous system (cf. (12,13,37,41,72)). They showed that EMS can cause significantly higher creatinkinase activity and thus might cause more damage in the individual's muscular system, which in turn would lengthen the regeneration time required between sessions.

In contrast to voluntary strength training, the MVC in EMS strength training is regulated according to the level of stimulation parameters. In turn, these parameters depend on the individual condition of the muscular system and on individual pain perception. In most EMS studies, 100% MVC was defined under voluntary maximal isometric conditions in an entry test. The level of stimulation intensity within the stimulation period was defined under EMS conditions and documented as a percentage of the MVC for the entry test performed under voluntary conditions. With regard to the MVC level, EMS research shows values of >100% with EMS. Under voluntary conditions, it is difficult to reach the absolute maximum level of contraction because accomplishing this depends on the individual's level of strength and motivation. Some studies revealed that elite athletes with a high level of maximal strength are able to reach levels of MVC close to the absolute maximum (100%). Average subjects only reach their maximum in extreme situations. For this reason, EMS could enable strength training at intensities that are otherwise difficult to reach because of the personal motivation levels. However, also in EMS training, the level of stimulation intensity (MVC) depends on individual pain perception with regard to the stimulation parameters and thus also indirectly depends on motivation.

In this review series, the selected studies, although collectively concerning the improvement of strength abilities, differed in stimulation patterns and training designs. More precisely, the studies vary in the type of EMS methods, training regimen, stimulation parameters, subject age and physical condition, group sizes, type of control groups, test designs, and parameters and in the EMS equipment used (EMS device and electrodes). All of these varying parameters in combination may influence the study outcome to a different degree and thus complicate the comparison of the results.

This second review out of our 2-part series reports data exclusively in relation to the results of the first study, which investigated the effects of EMS on selected strength parameters (cf. (30)). Therefore, the objectives of this second article are to examine the influence of the relevant training regimen and stimulation parameters on effectiveness; to identify a combination of training regimen and stimulation parameters for producing a stimulus that activates strength adaptations of the individuals' muscular system; to make recommendations for training control to enhance maximal strength, speed strength, and motor abilities such as jumping and sprinting.

METHODS

Search for and Selection of Eligible Studies

For the investigative process, we first concentrated on studies focussing on strength gains in skeletal muscles of healthy subjects with nonclinical background to filter the amount of EMS studies. As a result, about 200 studies were collected that were performed between 1965 and 2008. About 60% of them were found with the help of scientific search engines such as Medline and Pubmed and directly on journal data bases such as JSCR (Keywords: electrical stimulation, EMS, strength training, trained athletes, elite athletes). The other 40% were found through references within these studies.

To maximize the number of comparable trials (randomized controlled trails [RCTs]), certain preconditions were set: (a) Subjects: healthy, unimpaired subjects with ≤35 years of age; (b) Type of stimulation: percutaneous EMS with the aim of enhancing strength abilities of both the upper and lower body; and (c) Study design: minimum study duration of ≥7 days, comparable tests such as pretests, posttests, and retests.

Only studies with homogeneous groups on a comparable level of fitness were considered in this review. Significant gains for the training group were documented in relation to the baseline and the difference to the control group in posttesting (cf. (30)).

Data Classification

The review began by selecting a total of 59 studies. From this pool of investigations, all trials in which male and female subjects formed different training groups or in which >1 EMS group (with different EMS methods) was trained or tested with different parameters were once again divided into individual trails (cf., e.g., (21,60)). For example, studies investigated 2 types of EMS methods, the trials were split and each was sorted to a specific subgroup (e.g., isometric EMS, combination EMS).

All in all, 89 trials were emphasized from the original 59 studies. These trials were analyzed, compared, and presented in a comprehensive table.

To represent this large number of studies and their results clearly, the trials were classified according to the type of EMS method (local EMS methods–stimulation of defined muscle groups with single electrodes; whole-body EMS methods–stimulation and activation of several muscle groups simultaneously through an electrode belt system, agonist and antagonist are activated at the same time) and type of muscle contraction (e.g., isometric EMS, dynamic EMS [includes isokinetic]). The combination EMS method is a subgroup for both types of stimulation. In combination methods, the types described above are combined with additional specific training (e.g., conventional weight training, plyometric jump training).

Besides these categories, the review primarily differentiated between the subjects' individual levels of fitness: untrained subjects (no experience in strength training, no regular exercise before study); trained subjects (experience in strength training, regularly exercising up to 3 sessions per week); elite athletes (systematically training on a high-performance level >3 sessions per week).

Data Extraction

The data from the analyzed studies were sorted and presented in tables. To enable accurate categorization and to provide a layout for evaluating and comparing several different studies at the same time, all of the tables were based on the same parameters (cf. Tables 1 and 2).

Statistical Analyses

To analyze the data, different groups and subgroups were formed (cf. data classification). For evaluation, we assigned mean and *SD* of the data (training regimen and stimulation parameters) of meaningful studies in each category and subgroup. To compare the results and point out relationships between certain parameters, extreme data were eliminated.

Special focus was on trained and elite athletes. Untrained subjects were investigated for comparison purposes.

In references to significance levels or confidence intervals, an α-level of 0.05 was used, which corresponds to 95% confidence intervals. For correlation comparisons, the level of significance was established at $p \leq 0.05$.

RESULTS OF THE SEARCH AND SELECTION PROCESS

The analysis of the selected studies showed that more than half of the trials tested male subjects. Studies involving female subjects only or a mixed sample had a stake of 20%. Only 7 studies did not differentiate with details on gender.

On average, the subjects were 22.8 years old at the time of the pretest for the trials. All subjects were classified as healthy and unimpaired and had no history of injury in the tested muscle group. The trials covered a period between 10 days and 14 weeks. On average, 10.6 ± 5.1 subjects were examined over an average of 5 ± 2.3 weeks (cf. Table 3). However, the majority of the studies (68%) contained a stimulation period of 4–6 weeks. The number of training sessions varied from 1 to 7 sessions per week. An average of 16.3 ± 6.8 sessions was completed within the training period, with a duration of 17.6 ± 10.7 minutes per session (cf. Tables 4–6).

Regarding the locality of the stimulated muscles, the analysis showed that the lower body was the main object of the trials (75%). Furthermore, the study showed that the m. quadriceps femoris (60%) was the most examined muscle. In contrast, only

TABLE 1. Data extraction of subject information and training regimen.

	Subjects			Training regimen							
n	Sex	Age	Level of fitness	Sessions	Study period	Sessions per week	Contractions per session	Session duration	EMS method	Muscle type	Stimulation angle
Number of subjects per group	Gender	Ø Years of age	Untrained trained elite	Number of sessions (ses)	(wks)	Ses/wk	Number of contractions per session	(min)	Isometric, dynamic combination whole-body, etc.	QF, TS, BB, RA, TB, etc.	Fully extension = 180°

Ø = mean; QF = quadriceps femoris; BB = biceps brachii; RA = rectus abdominis; TB = triceps brachii.

Table 2. Data extraction of stimulation parameters.*

Stimulation parameters										
Type of current	Type of stimulator	Impulse form	Impulse width	Impulse frequency	Impulse intensity	Impulse on-time	Impulse interval	Duty-cycle	Rise/fall	Stimulation intensity
Biphasic Monophasic Alternating Russian Interference current	Type or brand of EMS stimulator	Sinus, rectangular, triangular, 2-peak, etc.	(μs)	(Hz)	(mA)	Contraction time on (s)	Time between 2 single impulses off (s)	Stimulation ratio, relation between on and off-time	Impulse, ramp time	Percentage maximum voluntary contraction

*EMS = electromyostimulation.

Table 3. Overview of mean values for the training regimen and stimulation parameters.*

	Training regimen								On-time	Interval	Intensity
89 Trials	Subjects	Age	Sessions	Weeks	Min	Width (μs)	Frequency (Hz)	Impulse intensity (mA)	On (s)	Off (s)	%MVC
Mean (*SD*)	10.6 (5.0)	22.9 (2.8)	16.5 (6.8)	5.1 (2.3)	17.7 (10.9)	266.3 (133.0)	68.8 (31.8)	59.6 (32.3)	10.2 (8.0)	42.4 (48.7)	59.5 (25.3)

*%MVC = percentage maximum voluntary contraction.

TABLE 4. Overview training regimen 1/3.

	Subjects				Training regimen							
Authors	*n*	Sex	Age	Level of fitness	Sessions	Weeks	Sessions per wk	Contractions/ sessions	*t* (min)	EMS method	Muscle	Stim
Avila, et al. (5)	10	W	20.9	Trained	8	4	2.0	3S/10Rep/3Int		Dynamic	QF	
Avila, et al. (5)	10	M	21	Trained	8	4	2.0	3S/10Rep/3Int		Dynamic	QF	
Speicher and Kleinöder (69)	10	M/W	23.19	Trained (sport student)	8	4	2.0	30		Iso/combination/ dyn WB	WB-EMS	150–100
Paillard I (60)	9	M	25.5	Trained (student)	15	5	3.0		15	Isometric	QF	90
Paillard II (60)	10	M	25.5	Trained (student)	15	5	3.0		60	Isometric	QF	90
Babault et al. (6)	15	M	22	Elite (rugby)	24	12	2.0	36	12	Isometric	QF/TS/GM	60/90/
Holcomb (33)	8	M/W	23.5	Trained (student)	12	4	3.0	15	15	Isometric	BB	90
Matsuse (52)	6	M	23.6	Untrained	24	8	3.0	100 Rep(conc)/ 100 rep(ecc)	16	Isometric	BB/TB	60
Jubeau et al. (38)	10	M	24	Untrained	16	4	4.0		18	Isometric	TS	90
Gondin et al. (31)	9	M	24.7	Untrained	32	8	4.0	40	18	Isometric	QF	120
Maffiuletti et al. (49)	1	M	29	Untrained	18	4	4.5	40	20	Isometric	QF	90
Boeckh-Behrens and Mainka (13)	22	M	22.9	Trained (sport student)	12	6	2.0		5	Iso WB	WB-EMS	
Boeckh-Behrens and Mainka II (13)	22	M	22.9	Trained (sport student)	12	6	2.0		10	Iso WB	WB-EMS	
Kreuzer (41)	9	M	16.78	Trained (water polo)	8	4	2.0		20	Iso/combination WB	WB-EMS	
Gondin et al. (31)	12	M	23.5	Untrained	32	8	4.0	40	18	Isometric	QF	120
Brocherie et al. (19)	9	M	22.6	Elite (ice hockey)	9	3	3.0	30	12	Isometric	QF	120
Boeckh-Behrens I (12)	21	M	22.3	Trained (sport student)	12	6	2.0		15	Iso WB	WB-EMS	
Boeckh-Behrens II (12)	20	M	22.3	Trained (sport student)	12	6	2.0		15	Iso WB	WB-EMS	
Herrero et al. (32)	11	M	19	Untrained	8	4	2.0	53	34	Isometric	QF	120
Herrero et al. (32)	10	M	19	Untrained	16	4	4.0	53	34	Isocombination	QF	120
Parker et al. (61)	7	M/W	23.2	Untrained	8	4	2.0	10	10	Isometric	QF	120
Parker et al. (61)	20	M/W	23.2	Untrained	12	4	3.0	10	10	Isometric	QF	120
Malatesta et al. (50)	12	M	17.2	Elite (volleyball)	12	4	3.0	20–22	12	Isometric	QF/TS	90/90
Boeckh-Behrens (14)	26	M	21.7	Trained (sport student)	12	6	2.0		45	Iso/combination WB	WB-EMS	
Dervisevic et al. (26)	20	M	24.2	Trained (sport student)	30	10	3.0		15	Iso/combination	QF	120
Bircan et al. (10)	10	M/W	23.2	Untrained	15	3	5.0		15	Isometric	QF	180
Bircan et al. (10)	10	M/W	23.2	Untrained	15	3	5.0		15	Isometric	QF	180
Bircan et al. (10)	10	M/W	23.2	Untrained	15	3	5.0		15	Isometric	QF	180

WB = whole-body.

Table 5. Overview training regimen 2/3.*

	Subjects				Training regimen							
Authors	*n*	Sex	Age	Level of fitness	Sessions	wks	Ses per wk	Contractions/sessions	*t* (min)	EMS method	Muscle	Stim
Maffiuletti et al. (47)	10	M	21.8	Elite (volleyball)	12	4	3.0	48/30 + 50Plyo	26	Combination	QF/TS	110/10
Maffiuletti et al. (47)	10	M	21.8	Elite (volleyball)	12	4	3.0	48/30	26	Isometric	QF/TS	110/10
Maffiuletti et al. (48)	8	M	20.4	Untrained	16	4	4.0	45	18	Isometric	TS/TA	90
Boeckhh-Behrens and Treu (15)	20	M	22.4	Trained (sports student)	12	6	2.0	5	25	Iso WB	WB-EMS	
Maffiuletti et al.	10	M	24.7	Elite (basketball)	12	4	3.0	48	16	Isometric	QF	120
Colson et al. (22)	9	M	24	Trained (student)	21	7	3.0	5S/6Rep/3Int		Isometric	BB	90
Hortobagyi et al. (35)	8	W	24.8	Untrained	24	6	4.0	35		Dyn (isokinetic)	QF	90 dyn
Willougby and Simpson (76)	5	W	20	Trained athletes	18	6	3.0			Isometric	QF	
Willougby and Simpson (76)	5	W	20	Trained athletes	18	6	3.0	3S/8–10Rep /3Int (85%1RM)		Dyn/isokinetic	QF	dyn
Hortogagyi et al. (34)	8	W	26.3	Untrained	24	6	4.0	4–6S/6–8Rep/1Int		Dyn (isokinetic)	QF	120
Willoughby and Simpson (75)	6	M	20	Elite (basketball)	18	6	3.0	10	10	Isometric	BB	180
Willoughby and Simpson (75)	6	M	20	Elite (basketball)	18	6	3.0	3S/8–10Rep/3Int	10	Dyn/isokinetic	BB	180°–30
Pichon et al. (62)	7		23	Elite (swimming)	9	3	3.0	27	12	Isometric	LD	140° arms
Martin et al. (51)	6	M	23.2	Untrained	12	4	3.0		10	Isometric	TS	Full dorsi flex
Miller and Thepaut-Mathieu (55)	16	M	23.3	Trained (student)	15	5	3.0	5S/5Rep/3Int		Isometric	BB	155
Balogun et al. (8)	10	M	22	Untrained	18	6	3.0	Max		Isometric	QF	120
Balogun et al. (8)	10	M	22	Untrained	18	6	3.0	Max		Isometric	QF	120
Balogun et al. (8)	10	M	23.1	Untrained	18	6	3.0	Max		Isometric	QF	120
Rich (64)	12	W	21		18	6	3.0			Isometric	TB	90
Rich (64)	12	M	21		18	6	3.0			Isometric	TB	90
Rich (64)	12	W	21		18	6	3.0			Isometric	BB	90
Rich (64)	12	M	21		18	6	3.0			Isometric	BB	90
Portmann and Montpetit (63)	11	W	24	Trained athletes	24	8	3.0	10		Dyn/isokinetic	QF	90–180
Portmann and Montpetit (63)	11	W	24	Trained athletes	24	8	3.0	10		Iso/combination	QF	90
Venable et al. (73)	13	M	19	Untrained	15	5	3.0	10	12	Iso/combination	QF	145/130/120
Delitto et al. (25)	1	M	27	Elite (weightlifter)	18	16	1.1	10	30	Isometric	QF	115
Soo et al. (68)	6	W	25.2		10	5	2.0	8		Isometric	QF	120
Soo et al. (68)	9	M	25.2		10	5	2.0	8		Isometric	QF	120
Lai et al. (43)	8	M/W	26.8	Untrained	15	3	5.0	3S/10Rep/1Int		Isometric	QF	120
Lai et al. (43)	8	M/W	23.3	Untrained	15	3	5.0	3S/10Rep/1Int		Isometric	QF	120
Cabric and Appell (21)	6	W	20	Trained (sports student)	14	2	7.0	10		Isometric	TS	10
Cabric and Appell (20)	12	M	21.5	Trained	21	3	7.0	15–25		Isometric	TS	10

*1RM = 1 repetition maximum; Dyn = dynamic; TS = triceps surae; QF = quadriceps femoris; RA = rectus abdominis; BB = biceps brachii; LD = latissimus dorsi; TB = triceps brachii; TA = tibialis anterior; UB = upper body; GM = gluteus muscles; WB = whole body.

TABLE 6. Overview training regimen 3/3.

	Subjects				Training regimen							
Authors	*n*	Sex	Age	Level of fitness	Sessions	Weeks	Ses per wk	Contractions/ sessions	t (min)	EMS method	Muscle	Stim°
Cabric and Appell (20)	12	M	21.5	Trained	21	3	7.0	15–25		Isometric	TS	10
Kubiak et al. (42)	10	M/W	24	Untrained	15	5	3.0	19		Isometric	QF	120
Alon et al. (1)	8	M/W	30	Untrained	12	4	3.0			Isometric	RA	0
Alon et al. (1)	8	M/W	30	Untrained	12	4	3.0			Isometric	RA	45
St. Pierre et al. (70)	3	W	20	Trained	7	1.5	4.7	10		Isometric	QF	90
St. Pierre et al. (70)	7	M	20	Trained	7	1.5	4.7	10		Isometric	QF	90
Weekslf et al.	9	M	33.2	Elite (tennis)	24	6	4.0	5 Set of max*V* diff °s		Dyn/isokinetic	QF	
Nobbs et al. (57)	9	W	20.89	Trained (student)	18	6	3.0	10		Dyn (isokinetic)	QF	45
Nobbs et al. (57)	9	W	21.22	Trained (student)	18	6	3.0	3S/6Rep		Dyn (isokinetic)	QF	90–180
Selkowitz (67)	8	M/W	24.6	Trained (student)	12	4	3.0	10		Isometric	QF	120
Boutelle et al. (17)	9	M/W	26		20	4	5.0	10		Isometric	QF	150
Stefanovska Vodovnik (71)	5		22.5	Untrained	24	4	6.0		10	Isometric	QF	120
Stefanovska Vodovnik (71)	5		22.5	Untrained	24	4	6.0		10	Isometric	QF	120
Mohr et al. (56)	6	W	25	Untrained	15	3	5.0	10		Isometric	QF	120
Fahey et al. (29)	19	M	27.5	Untrained	18	6	3.0		15	Isometric	QF	115
Fahey et al. (29)	19	M	27.5	Untrained	18	6	3.0		15	Isometric	QF	180
Currier and Mann (24)	8	M/W	24	Untrained	15	5	3.0	10		Isometric	QF	120
Currier and Mann (24)	9	M/W	24	Untrained	15	5	3.0	10		Isometric	QF	120
Laughman et al. (45)	20	M/W	23.5	Untrained	25	5	5.0	10	12.50	Isometric	QF	120
Owens and Malone (59)	10	M/W	21	Untrained	10	1.5	6.7	10		Isometric	QF	145
Owens and Melone (59)	10	M/W	21	Untrained	5	1.5	3.3	10		Isometric	QF	145
McMiken et al. (54)	9	M/W	21.3		10	3	3.3	10		Isometric	QF	150
Romero et al. (65)	9	W	21.6	Untrained	10	5	2.0		15	Isometric	QF	115
Eriksson et al. (28)	9		20	Trained (student)	25	5	5.0	ca. 24	12	Isometric	QF	90
Eriksson et al. (28)	4		22	Trained (student)	15	4	3.8	6	6	Isometric	QF	90
Kots and Chwilon (39)	16		17	Trained (judo)	16	2.5	6.4	10	10	Isometric	TS	
Kots and Chwilon (39)	19				16	2.5	6.4	10	10	Isometric	TS	
Anzil et al. (2)	10	M	18	Untrained	52	8	6.5			Isometric	QF	90
Massey et al. (52)	16	M	22	Trained (marines)		9			40	Isometric	UB	Diff.
Mean value (*SD*)	10.6 (4.9)		22.8 (2.8)		16.3 (6.9)	5.0 (2.2)	3.5 (1.4)		17.5 (10.5)			108.1 (39.3)

Table 7. Overview EMS parameters 1/3.*

	Stimulation parameters										Stimulation intensity	
Authors	Type of current	Type of stimulator	Impulse form	µs	Hz	mA	on(s)	off(s)	Duty	Rise/fall	%MVC	ø
Avila et al. (5)	Russian current	Physiotonus Slim, Bioset, Brazi	Sinus	200	50	44						
Avila et al. (5)	Russian current	Physiotonus Slim, Bioset, Brazi	Sinus	200	50	58						
Speicher et al. (69)	Biphasic	Miha Bodytec	Rectangular	350	85		60	60	50.0			
Paillard I (60)	Biphasic	CEFARTM MYO 4, Sweden	Rectangular	450	80	60.8	6	18	25.0	1.8/1.2		
Paillard (60)	Biphasic	CEFARTM MYO 4, Sweden	Rectangular	450	25	67.6	10	6	62.5	1.8/1.2		
Babault et al. (6)	Biphasic	Compex Medical SA	Rectangular	400	100	50	5	15	25.0		60	60
Holcomb (33)	Russian current	Forte 400 Combo E-Stimulator	Sinus		90		15	45	25.0		20.4	20.4
Matsuse et al. (53)	Biphasic		Rectangular		20	10	2				25–30	27.5
Jubeau et al. (38)	Biphasic	Compex Medical SA	Rectangular	400	75	70.5	6.25	20	23.8	1.5/0.75	82 ± 19	82
Gondin et al. (31)	Biphasic	Compex Medical SA	Rectangular	400	75	72.5	6.25	20	23.8	1.5/0.75	68 ± 14	68
Maffiuletti et al. (49)	Biphasic	Compex Medical SA	Rectangular	400	75	64	6.25	20	23.8	1.5/0.75	61–79	70
Boeckh-Behrens and Mainka (13)	Biphasic	Body Transformer	Rectangular	350	80		4	4	50.0	0/0		
Boeckh-Behrens and Mainka (13)	Biphasic	Body Transformer	Rectangular	350	80		4	4	50.0	0/0		
Kreuzer et al. (41)	Biphasic	Body Transformer	Rectangular	350	85		4	4	50.0			
Gondin et al. (31)	Biphasic	Compex Medical SA	Rectangular	400	75	75	4	20	16.7	1.5/0.75	68 ± 13	68
Brocherie et al. (19)	Biphasic	Compex 2 Medical SA	Rectangular	250	85		4	20	16.7		60	60
Boeckh-Behrens and Bengel (12)	Biphasic	Body Transformer	Rectangular	350	80		4	4	50.0	0/0		
Boeckh-Behrens and Bengel (12)	Biphasic	Body Transformer	Rectangular	350	80		4	10	28.6	0/0		
Herrero et al. (32)	Biphasic	Compex Medical SA	Rectangular	400	120	40	3	30	9.1	0.75/0.5		
Herrero et al. (32)	Biphasic	Compex Sport Medical SA	Rectangular	400	120	66	3	30	9.1	0.75/0.5		
Parker et al. (61)		Forte 200 electrical stimulator		200	50	82.8	10	50	16.7		63	63
Parker et al. (61)		Forte 200 electrical stimulator		200	50	75.3	10	50	16.7		69.5	69.5
Malatesta et al. (50)	Biphasic	Compex 2 Medical SA	Rectangular	400	120	80	4.25	31.5	11.9	0.7/0.5		
Boeckh-Behrens et al. (14)	Biphasic	Body Transformer	Triangular	350	80		8	4	66.7	0.3/0		
Dervisevic et al. (26)		BIMED 999S									10	10
Bircan et al. (10)	Interference current	Myomed 932	Sinus		80	44	13	50	20.6	2/1s		
Bircan et al. (10)	Interference current	Myomed 932	Sinus		80	43.5	13	50	20.6	2/1s		
Bircan et al. (10)	Biphasic symmetr.	Myomed 932		100	80	44	13	50	20.6	2/1s		

*EMS = electromyostimulation.

TABLE 8. Overview EMS parameters 2/3.

	Stimulation parameters										Stimulation intensity	
Authors	Type of current	Type of stimulator	Impulse form	µs	Hz	mA	on (s)	off (s)	Duty	Rise/fall	%MVC	ø
Maffiuletti et al. (47)	Biphasic	Compex Sport Medical SA	Rectangular	400	120	90	3	17	15.0	0.75/0.5	60	60
Maffiuletti et al. (47)	Biphasic	Compex Sport Medical SA	Rectangular	400	120	90	3	17	15.0	0.75/0.5	60	60
Maffiuletti et al. (48)	Biphasic	Compex Sport Medical SA	Rectangular	400	75	60	4	20	16.7		50–70	60
Boeckhh-Behrens and Treu (15)	Biphasic	Body Transformer	Triangular	350	80		8	4	66.7	0.3/0		
Maffiuletti et al. (46)	Biphasic	Compex 2 Medical SA	Rectangular	400	100	80	3	17	15.0		80	80
Colson et al. (22)	Biphasic	Compex 2 Medical SA	Rectangular	240	80	100	3				60–70	65
Hortobágyi et al. (35)	Alternating current	Electrostim 180-2	Sinus		50	52.5			50.0		49–106	77.5
Willougby and Simpson (76)		Dynatron 500	Sinus	100	50		25	180	12.2			
Willougby and Simpson (76)		Dynatron 500	Sinus	100	50		25	180	12.2			
Hortobágyi et al. (34)	Biphasic	Electrostim 180-2	Sinus		50	52			50.0		70–150	110
Willoughby and Simpson (75)		Dynatron 500	Symmetric	100	50		30	120	20.0		85	85
Willoughby and Simpson (75)		Dynatron 500		100	50		30	120	20.0		85	85
Pichon et al. (62)	Biphasic	Stiwell Stimulator	Rectangular	300	80		6	20	23.1		60	60
Mmethodin et al.	Alternating current	Compex Sport Medical SA		200	70		5	15	25.0		63.2 ± 8.6	63.2
Miller and Thepaut-Mathieu (55)	Monophasic	Prototype Uni. Compiegne	Rectangular	200	90	59.9	5	25	16.7	1-2/	30.6	30.6
Balogun et al. (8)	Monophasic	HVGS	2-Peak (needle)	70	20		10	50	16.7			
Balogun et al. (8)	Monophasic	HVGS	2-Peak (needle)	70	45		10	50	16.7			
Balogun et al. (8)	Monophasic	HVGS	2-Peak (needle)	70	80		10	50	16.7			
Rich (64)	Russian current	Electrostim 180-2	Sinus	100	50	18.4	10	50	16.7	5/0	62.3	62.3
Rich (64)	Russian current	Electrostim 180-2	Sinus	100	50	34	10	50	16.7	5/0	45.5	45.5
Rich (64)	Russian current	Electrostim 180-2	Sinus	100	50	42.8	10	50	16.7	5/0	37.2	37.2
Rich (64)	Russian current	Electrostim 180-2	Sinus	100	50	54.7	10	50	16.7	5/0	29.6	29.6
Portmann and Montpetit (63)	Monophasic comp	BMR Powerstim	Rectangular	400	100		10	50	16.7		82.2–93.6	87.9
Portmann and Montpetit (63)	Monophasic comp	BMR Powerstim	Rectangular	400	100		10	50	16.7		81.1–94.8	87.9
Venable et al. (73)	Biphasic	Intelect VMS Stimulator	Rectangular	200	50		15	60	20.0	5/0	33–110	71.5
Delitto et al. (25)		VersaStim 380 Miami	Triangular		75	200	11	180	5.8		112	112
Soo et al. (68)	Russian current	Electrostim 180-2	Sinus		50	40	15			5/0	50	50
Soo et al. (68)	Russian current	Electrostim 180-2	Sinus		50	40	15			5/0	50	50
Lai et al. (43)	Biphasic asymetr.	Minidyne 3 UK	Asymmetric	200	50		5	5	50.0		56.6–72.7	64.6
Lai et al. (43)	Biphasic asymetr.	Minidyne 3 UK	Asymmetric	200	50		5	5	50.0		43.4–60.5	52
Cabric and Appell (21)	Alternating current		Rectangular	150	2,500	40	10	50	16.7			
Cabric and Appell (20)	Alternating current		Rectangular	200	50	40	5	35	12.5			

TABLE 9. Overview EMS parameters 3/3.*

Authors	Stimulation parameters				
	Type of current	Type of stimulator	Impulse form	µs	Hz
Cabric and Appell (20)	Alternating current		Rectangular	200	2000
Kubiak et al. (42)	Russian current	Electrostim 180-2	Sinus		50
Alon et al. (1)	Biphasic symmetr.	Intelect VMS stimulator Proto	Symmetric	200	50
Alon et al. (1)†	Biphasic symmetr.	Intelect VMS stimulator Proto	Symmetric	200	50
St. Pierre et al. (70)	Alternating current	Dr. Kots personal apparatus	Sinus		50
St. Pierre et al. (70)	Alternating current	Dr. Kots personal apparatus	Sinus		50
weekslf et al.	Monophasic	EMPI, Inc., Fridley, MN	Rectangular		75
Nobbs and Rhodes (57)	Faraday Strom	Model F283, Multitone Electric	Rectangular		60
Nobbs and Rhodes (57) isokinetic.	Faraday Strom	Model F283, Multitone Electric	Rectangular		60
Selkowitz (67)	Russian current	Electrostim 180-2	Sinus	450	50
Boutelle et al. (17)	Russian current	Electrostim 180	Sinus		50
Stefanovska and Vodovnik (71)	Monophasic		Sinus	300	25
Stefanovska and Vodovnik (71)	Monophasic		Rectangular	300	25
Mohr et al. (56)	Monophasic	Intellect Model 500 HVG	2-Peak (needle)	45	50
Fahey et al. (29)	Biphasic asymetr.	Medtronic 3108	Rectangular		50
Fahey et al. (29)	Biphasic asymetr.	Medtronic 3107	Rectangular		50
Currier and Mann (24)	Russian current	Electrostim 180-2	Sinus	100	50
Currier and Mann (24)	Russian current	Electrostim 180-2	Sinus	100	50
Laughman et al. (45)	Russian current	Electrostim 180	Sinus		50
Owens and Melone (59)	Russian current	Electrostim 180	Sinus	200	50
Owens and Melone (59)	Russian current	Electrostim 180	Sinus	200	50
McMiken et al. (54)	Faraday Strom	Faradic Unit Model GF01		100	75
Romero et al. (65)	Faraday Strom	SP5 Faradic			2,000
Eriksson et al. (28)		Grass. Quincy. Mass	Rectangular	500	200
Eriksson et al. (28)		Grass, Quincy, Mass	Rectangular	500	200
Kots and Chwilon (39)	Russian current	Dr. Kots personal apparatus	Rectangular		50
Kots and Chwilon (39)	Russian current	Dr. Kots personal apparatus	Rectangular		50
Anzil et al. (2)*		Modotto personal stimulator			
Massey et al. (52)		Isotron stimulator	Rectangular		1,000
Mean value (*SD*)				261.6 (131.9)	151.4 (399.5)

Authors	Stimulation parameters					Stimulation intensity	
	mA	on (s)	off (s)	Duty	Rise/fall	%MVC	ø
Cabric and Appell (20)	40	5	35	12.5			
Kubiak et al. (42)		15	50	23.1	5/0	75	75
Alon et al. (1)	122	12.5	7.5	62.5			
Alon et al. (1)†	122	12.5	7.5	62.5			
St. Pierre et al. (70)	39.5	10	50	16.7		80–100	90
St. Pierre et al. (70)	39.5	10	50	16.7		80–100	90
weekslf et al.	62					20–40	30
Nobbs and Rhodes (57)	15.00	10	50	16.7			
Nobbs and Rhodes (57) isokinetic.†	15.00	3	50	5.7			
Selkowitz (67)	59	10	120	7.7	0.6–3/	91	91
Boutelle et al. (17)							
Stefanovska and Vodovnik (71)	73.1	10	50	16.7		5	5
Stefanovska and Vodovnik (71)	43.12	10	50	16.7		5	5
Mohr et al. (56)		10	10	50.0	3.3/0		
Fahey et al. (29)	45	10	5	66.7	2/0		
Fahey et al. (29)	45	10	5	66.7	2/0		
Currier and Mann (24)†	45.8	15	50	23.1	5/0	66.7	66.7
Currier and Mann (24)	55.3	15	50	23.1	5/0	88.4	88.4
Laughman et al. (45)	62.5	15	50	23.1	5/0	33	33
Owens and Melone (59)	46.5	15	50	23.1	3.5/	60	60
Owens and Melone (59)	34.6	15	50	23.1	3.5/	39	39
McMiken et al. (54)		10	50	16.7		80	80
Romero et al. (65)		4	4	50.0			
Eriksson et al. (28)		15	15	50.0			
Eriksson et al. (28)		6	6	50.0			
Kots and Chwilon (39)		10	50	16.7		>50	50
Kots and Chwilon (39)		10	50	16.7		>50	50
Anzil et al. (2)*		10	300	3.2			
Massey et al. (52)		10					
Mean value (*SD*)	58.6 (30.5)	10.1 (7.9)	40.8 (38.2)	27.0 (17.5)			60.8 (24.8)

*EMS = electromyostimulation.

17% of the studies investigated the upper body. Beyond that, only 8% analyzed the effects of whole-body stimulation on the muscle (12–15,41,66,69) (cf. Tables 4–6).

Besides these basic data, the analysis performed during this study showed that several parameters are used to influence stimulation effectiveness (i.e., the training outcome).

Impulse Type

Analysis of the selected studies revealed a large deviance in the types of EMS stimulators used. A stimulator produced by the company "Compex" was used in 37% of the trials conducted after 1994. Before then, an "Electrostim 180" device was used (28%). In the recent years, new stimulators, such as the "Bodytransformer" or the EMS stimulator manufactured by "Miha Bodytec" have been in use for whole-body EMS.

The impulse type that these EMS stimulators produced in the selected studies was biphasic in 40% of the cases and monophasic in 12%. In 21% of the trials, a so-called "Russian current" was used. This type of impulse was delivered by the "Electrostim 180." An alternating sinus current was applied in only 8% of the studies. Furthermore, only 5% of the trials were accomplished with an Interference or Faraday current. The rest of the studies (15%) provided no information about the impulse type used.

It is noteworthy that, from 1994 onward, most of the trials (67%) used biphasic impulses (cf. Tables 5–9).

Impulse Form

Forty percent of the impulses were delivered with a square or rectangular form, and another 27% used an alternating sinus impulse form. In 15% of the studies, stimulation was performed with symmetrical, asymmetrical, triangular, and peak impulses. The rest of the trials (10%) did not comment on the impulse form.

Impulse Width

On average, an impulse width of 261 ± 132 microseconds was used. A width between 200 and 400 microseconds was applied in 48% of the study designs. In 27% of the studies, no information about impulse width was provided.

Impulse Frequency

The regulated frequency varied between 25 and 2,500 Hz. Frequencies over 1,000 Hz were not included in the mean value (cf. (21,52,65)).

Impulse Intensity

To regulate the maximum impulse intensity, this value was either defined as the maximal tolerated amperage or as the maximal comfortable amperage (mA). This value varied between 10 and 200 mA.

Impulse on Time

In the sample of trials, the time over which a single impulse stimulated a muscle group varied between 3 and 60 seconds. The interval between 2 impulses varied between 4 seconds and 3 minutes.

Stimulation Intensity

Intensity was defined and regulated on the basis of the MVC during the retest of a particular muscle and expressed as a percentage. The values ranged between 5 and 112% of the MVC (cf. Tables 5–9). In 42% of the studies, no information was provided on the intensity in relation to the MVC.

COMPARISON OF CERTAIN TRAINING REGIMENS AND THEIR TRAINING EFFECTIVENESS

Studies reviewed in this section applied a stimulation intensity of 63.2 ± 19.8% MVC and documented significant strength gains ($p < 0.05$) in maximal strength, speed strength, jumping and sprinting ability, and power.

Duration of Training Period

As far as the training period is concerned, the authors achieved significant gains in maximal strength within 3–6 weeks (3.2 ± 0.9 sessions per week) of duration regardless of the local EMS method and the subject's level of fitness (e.g., gains in isometric *F*max after isometric EMS: trained athletes 4.3 ± 1.9 weeks (20–22,28,55,63,67); elite athletes 3.5 ± 0.7 (46,62)). Moreover, it was possible to reveal that an extension of the training period beyond 6 weeks without varying the stimulus shows no further significant strength gains ($p < 0.05$). Only one study was able to achieve an increase in isometric *F*max with <3 weeks of stimulation (21).

The analysis of the effects on jumping ability revealed that a stimulation period of as many as 4 weeks is adequate for enhancing jumping strength (trained subjects, elite athletes 4.4 ± 1.5 weeks (6,39,46,60)). For example, Brocherie et al. (19) documented a decrease in jumping values (SJ −8.4; CMJ −6.1; DJ −4.8) within 3 weeks of study duration (3 sessions per week) although they used stimulation parameters similar to the ones employed in other successful trials (cf. 6,39,46,50,60,75,76).

In summary, regardless of the EMS method used, the analysis revealed that a stimulation period in a range of 4–6 weeks (3.2 ± 0.9 sessions per week) shows positive effects for enhancing strength parameters, jumping and sprinting ability, and power.

Number of Stimulation Sessions per Week

Regarding strength gains achieved with local EMS methods (isometric EMS, dynamic EMS), the analysis showed that 3 sessions per week (over 4–6 weeks) can be adequate to achieve significant gains in isometric *F*max >30% in trained subjects (isometric EMS 4.8 ± 2 sessions per week (20–22, 28,55,63,67); dynamic EMS 3 ± 0 sessions per week (57,63)) and elite athletes (isometric EMS 3.5 ± 0.7 sessions per week (46,62); combination EMS 3 ± 0 sessions per week plus 3 ± 0 sessions per week of additional plyometric jump training (47)).

The studies by Parker et al. (61) and Soo et al. (68) indicated that less than 3 sessions per week (2 ± 0) might not suffice to activate strength adaptations. However, the analysis of the results could not show a correlation between the number of stimulation sessions per week and the strength gains in isometric *F*max. The same results were found and transferred in all EMS methods.

In the view of dynamic *F*max, the analysis documented strength gains of >30% with local EMS methods in trained subjects and elite athletes (isometric EMS 3.8 ± 2.2 sessions per week (6,25,39,75); dynamic EMS 3 ± 0 sessions per week (75,76)).

The use of 3 sessions per weeks could also be seen in studies focussing the *M*max. The analysis documented significant gains in concentric and eccentric *M*max of trained subjects training 3.3 ± 0.5 sessions per week with isometric EMS (22,26,28,63) and 2.5 ± 0.6 sessions per week with dynamic EMS (5,57) and elite athletes training 2.8 ± 0.5 sessions per week in isometric EMS (6,19,46,62) and 3.5 ± 0.7 sessions per week in dynamic EMS (75,77).

Regarding the whole-body EMS methods, the analysis showed that all trials using whole-body EMS only used 2 stimulation sessions per week (2 ± 0 sessions per week (12–15,41,66,69). These studies only achieved minor increases in maximal strength (isometric *F*max <10%; dynamic *F*max <10%) and in jumping ability (not significant). However, studies showed that power (*P*max) and parameters of speed strength (RFD; force impulse) can be significantly developed with 2 sessions per week over a 4-week stimulation period (cf. (66,74)).

In summary, the present investigation reveals that applying an EMS stimulus above training threshold ≥3 times a week (over 4.4 ± 1.5 weeks) shows positive effects for enhancing strength parameters. To ensure regeneration and to not overstress the subjects muscular system, we recommend not to exceed 3 sessions per week for enhancing the strength parameters at hand.

Duration of a Stimulation Session

On the basis of results from meaningful studies, the analysis revealed that an average stimulation duration of 17.52 ± 10.56 minutes in each of 3 sessions per week (3.2 ± 0.9 sessions per week, 4–6 weeks) with a sufficient intensity can be adequate to activate strength adaptations with EMS methods (isometric EMS 16.5 ± 10 minutes; combination EMS 25.3 ± 12.4; whole-body EMS 14.0 ± 7.4).

Regarding strength gains in maximal strength, the analysis showed that elite athletes increased the isometric *F*max >20% with isometric EMS by using a stimulation duration of 14.0 ± 2.8 minutes per session (46,62) and trained subjects with 11 ± 1.4 minutes per session (28,63). For significantly increasing dyn *F*max Portmann and Montpetit (63) applied dynamic EMS of 10 minutes per session (3 sessions per week). Increase in dyn *F*max in trained and elite athletes with isometric EMS was achieved with a stimulation duration of 15.5 ± 9.7 minutes per session (3.8 ± 2.2 sessions per week) (6,25,39,75).

Regarding gains in vertical jump in trained and elite athletes the analysis showed that significant increases were achieved with a stimulation duration of 13.3 ± 2.8 minutes (4 ± 2 sessions per week) in isometric EMS (6,39,46,60) and with 24.0 ± 11.1 minutes per session with combination EMS (32,47,73). Similar results were shown in sprint ability of elite athletes using isometric EMS (12.0 ± 0 minutes per session (19,62)).

In comparison, the results of trials using whole-body EMS methods showed that a duration of 15 minutes can be assumed to be sufficient for stimulation to activate strength adaptations and thus increasing strength abilities (e.g., dyn *F*max 11.8 ± 5.7 (12,13,15)). No significantly higher increases were found because of a longer stimulation duration per session (cf. (14,69)). The investigation further revealed a significant correlation ($p \leq 0.05$) between stimulation duration for whole-body isometric EMS (5–15 minutes) and the increase of dynamic Fmax within a duty cycle of <50% (50–28.6%), which supports the previous thesis. Furthermore, the whole-body EMS methods can simultaneously stimulate several muscle groups at the same time (15 minutes), whereas local methods only stimulated one muscle group.

In summary, a stimulation duration in the range of 10–15 minutes appears to be sufficient for enhancing the current strength parameters with all of the analyzed EMS methods.

COMPARISON OF CERTAIN ELECTROMYOSTIMULATION PARAMETERS AND CORRELATION TO TRAINING EFFECTIVENESS

All studies reviewed in the following section documented significant strength gains ($p < 0.05$) by applying EMS over a stimulation period of 4.4 ± 1.5 weeks with 3.2 ± 0.9 session per week.

Stimulation Intensity

The analysis in this study revealed that training intensity is the primary parameter for training effectiveness. It was possible to show that the level of stimulation intensity (MVC) of the trained muscle determines the training effectiveness. According to this, the analysis demonstrated a significant correlation ($r = 0.724$, $p < 0.05$) between %MVC (65.2 ± 7.6% MVC) and the strength gain in isometric *F*max (29.1 ± 8.0%) for trained subjects after isometric EMS (cf. (20–22,28,32,52,55,63,67)). A significant correlation ($r = 0.433$, $p < 0.05$) with the same parameters could be seen in untrained subjects as well (63.6 ± 16.4% MVC (2,8,17,24,31,32,38,42,43,45,47,49,51,53,54,56,59,61,68,71)).

Regarding significant strength gains in isometric *F*max with local isometric EMS, meaningful studies applied a stimulation intensity of 68.6 ± 27.9% MVC in trained subjects (20–22,28,55,63,67) and 70 ± 14.1% MVC in elite athletes (46,62). Similar results were shown in dynamic EMS (trained subjects 87.9% MVC (63)); and isometric combination EMS (elite athletes 60.0% MVC (47)). In regard to increases in vertical jump height with isometric EMS meaningful studies achieved significant gains with ≥50% MVC in trained subjects (39,60) and with 57.0 ± 4.1% MVC in elite athletes (6,46). Similar MVC values were documented in studies using combination EMS for enhancing jump ability (65.8 ± 8.1% MVC (47,73)).

In studies investigating whole-body EMS methods no information about the level of MVC was given (12–15,41,66,69).

According to the results, in all of the analyzed categories, significant positive changes can be related to an MVC level of ≥50%. Holcomb (33) and Stefanoska and Vodovnik (71) confirm these results. The stimulation intensity (MVC) they used (20.4%; 5% MVC) was too low to produce a stimulus above the training threshold to cause strength adaptations. Furthermore, in the study by Rich et al. (64) significant strength increases in isometric *F*max were only achieved in the group for which a stimulation intensity of >50% MVC was applied.

In summary, it can be assumed that a stimulation intensity of ≥50% MVC is required to produce a stimulus in the muscles that has a sufficient intensity to activate strength adaptations. The analysis further showed that the MVC level is mainly influenced by the impulse intensity (mA), the stimulation frequency (Hz) and the impulse width (microseconds). For the sum of these stimulation parameters, there is a recommendable range or level, which will be given below.

Impulse Intensity

Regarding the effect of isometric EMS on isometric *F*max, the analysis showed a significant relationship ($p < 0.05$) between impulse intensity (mA) and the muscle contraction (MVC) in untrained subjects (1,2,8,17,24,31,38,42,43,45,51,53,54,64,68). The results reveal the influence of impulse intensity (mA) on stimulation intensity (%MVC).

Regarding significant strength gains in isometric *F*max with local EMS methods, meaningful studies applied an impulse intensity of ≥40 mA (trained subjects 56.5 ± 23.4 mA (20–22,55,67); elite athletes 80 mA (46)). Similar results were shown in studies focusing isokinetic *M*max in trained subjects and elite athletes. (e.g., isometric EMS 65.0 ± 21.2 mA (6,46); dynamic EMS 53.7 ± 6.8 mA (5,34,35,77)) and jumping ability (e.g., isometric EMS 63.5 ± 15.2 mA (6,46,60)).

In studies investigating whole-body EMS methods no information about the level of impulse intensity (mA) was given (12–15,41,66,69).

Nonetheless, the analysis showed that high MVC levels (and consequently significant strength gains) were predominately achieved with an impulse intensity of ≥50 mA. However, it is difficult to quantify this, because the impulse intensity (mA) is influenced by several individual factors such as tissue structures and pain perception.

In summary, the analysis revealed that an impulse intensity of ≥50 mA positively influences the generation of a stimulation intensity of ≥50% MVC.

Impulse Frequency

The present analysis showed evidence that an impulse frequency of ≥50 Hz is a precondition for developing a high stimulation intensity (%MVC) and thus for producing a training stimulus that activates strength adaptations. The studies at hand showed significant gains in strength parameters and jumping and sprinting ability by a use of 68.6 ± 31.7 Hz on average.

Studies focussing the increase of isometric *F*max with local EMS methods used stimulation frequencies of ≥50 Hz in trained subjects (isometric EMS 80 ± 21.6 Hz (21,22,55,63); dynamic EMS 80 ± 28.3 Hz (57,63)).

Similar frequencies were shown in studies that significantly increased dynamic Fmax of elite athletes (isometric EMS 68.0 ± 23.9 Hz (6,25,39,75); dynamic EMS 62.5 ± 17.7 Hz (76,77)).

Also, in studies focusing on isokinetic *M*max a stimulation frequency of ≥50 Hz could be seen in trained subjects (isometric EMS 68.7 ± 11.5 Hz (22,26,63); dynamic EMS 60.0 ± 20.0 Hz (5,34,35,57,63)) and elite athletes (isometric EMS 91.3 ± 10.3 Hz (6,19,46,62); dynamic EMS 62.5 ± 17.7 Hz (75,77)).

Regarding performance, independent of the subjects' level of fitness, significant gains in jumping ability were achieved by the use of 82.5 ± 23.6 Hz in isometric EMS (6,39,46,60) and by 95.8 ± 39.7 Hz in combination EMS (32,47,73). Furthermore, it was possible to increase the sprint strength with a stimulation frequency of 82.5 ± 2.5 Hz in isometric EMS (elite athletes (19,64)) and 120.0 Hz in combination EMS (untrained (33)).

In comparison to local EMS methods, studies using whole-body EMS methods applied a stimulation frequency of ≥ 80 Hz (82.5 ± 3.5 Hz (12–15,41,66,69) and achieved significant gains in maximal strength of ≤10% (isom *F*max/dyn *F*max), speed strength (RFD; force impulse) and power of trained subjects.

In summary, according to the results of this study, we can suggest that independent of the EMS method a stimulation frequency of ≥60 Hz can be sufficient for developing a high stimulation intensity (MVC) to enhance maximal strength, speed strength, power, and jumping and sprinting ability.

Impulse Width

Regarding the level of impulse width (microseconds), several authors recommend the use of a medium-width (cf. (16)). Accordingly, in this review overall, 48% of the trials used impulse widths of 200–400 microseconds (261.64 ± 131.88 microseconds, e.g., (14,32,37,38,46,49)).

The analysis showed that impulse width influences the intensity of muscle contraction (%MVC) when combined with the abovementioned stimulation parameters in the recommended range. However, it was not possible to show any direct correlation between impulse width and %MVC. For example, the studies performed by Willoughby and Simpson (75) and by Portmann and Montpetit (63) achieved intensities of >85% MVC with an impulse width of 100 microseconds and 400 microseconds.

Compared to the impulse widths used in isometric EMS (isom *F*max 292.5 ± 135.3 microseconds (20–22,27,55,63,67); dyn *F*max 350.0 ± 70.7 microseconds (46,62); isok *M*max 345.0 ± 127.9 microseconds (22,26,28,63); vertical jump 416.7 ±

28.9 microseconds (6,46,60); sprint time 275.0 ± 25.0 microseconds (19,62)) narrower impulses were generally noticeable in studies using dynamic EMS (dyn *F*max 200.0 ± 173.2 microseconds (63,75,76); isok *M*max 200.0 ± 122.5 microseconds (5,63,75,76); vertical jump 100 microseconds (76)). Depending on the type of combination EMS method (isometric, dynamic) similar impulse widths were used (e.g., isometric *F*max 333.3 ± 115.5 microseconds; isometric combination EMS (32,47,73)).

Similar to local EMS methods whole-body EMS studies also applied a medium-width impulse of 350.0 ± 0 microseconds (12–15,41,66,69)) and achieved significant gains in maximal strength of ≤10% (isom *F*max/dyn *F*max), speed strength (RFD; force impulse) and power in trained subjects.

On the basis of the results of the present analysis we assume that impulse widths in a range of 200–400 microseconds are sufficient for producing a stimulus above training threshold and thus activate strength adaptations.

Stimulation Ratio (Duty Cycle)

The stimulation ratio (duty cycle) is defined as ratio of on-time to the total cycle time (% duty cycle = 100/[total time/on-time]).

Regarding the stimulation ratio (duty cycle) in local EMS methods, the analysis showed that a duty cycle between 20 and 25% shows positive effect on strength enhancements. It was possible to reveal a significant correlation ($p < 0.5$) between a duty cycle of 26.5 ± 13.7% within isometric EMS and strength gains in isometric *F*max for untrained subjects (23.5 ± 8.9% duty cycle (1,2,8,15,24,31,38,42,43,45,51,53,54,64,68)).

In regard to the enhancement in isom *F*max (32.3 ± 16.6%) with isometric EMS, similar duty cycles were documented in trained subjects (19.0 ± 14.1% duty cycle (20,21,28,55,63,67)) and elite athletes (19.1 ± 5.7% duty cycle (46,62)). Similar duty cycles were also found in studies that significantly increased isokinetic *M*max (19.9 ± 4.8% duty cycle (6,19,46,62)), jumping (20.4 ± 5.3% duty cycle (6,39,46,60)), and sprinting ability (19.9 ± 3.1% duty cycle (19,62)) with isometric EMS. In addition, in studies using dynamic EMS a duty cycle in the same range was favored (e.g., dyn *F*max 16.1 ± 5.5% duty cycle (75,76); jumping ability 12.1% duty cycle (76)).

The combination EMS methods revealed that significant gains up to +62% in isometric *F*max are possible with a duty cycle of 14.7 ± 5.5% (32,47,73) when supplemented by traditional strength training (2.7 ± 0.6 sessions per week (40,57,86)).

In the case of the whole-body EMS method, a stimulation design with a duty cycle between 28.6 and 66.7% was used (12–15,41,69). Whole-body EMS methods documented significant gains in maximal strength, speed strength (RFD; force impulse), and power. No gains in vertical jump ability could be documented.

Regarding the on-time (contraction time), the analysis showed that impulse on-times of 3–10 seconds in particular positively influence strength adaptations in trained subjects and elite athletes when using isometric EMS method (e.g., isom *F*max 7.8 ± 3.7 seconds (7,31,42,43,51); dyn *F*max 6.3 ± 3.5 seconds (22,26,28,63); vertical jump 6.0 ± 2.9 seconds (6,39,46,60); sprint 5.0 ± 1.0 seconds (19,62)). Concerning dynamic EMS methods Willoughby and Simpson (75,76) achieved significant gains >20% in dyn *F*max and vertical jump by using longer impulse on-times ≥20 seconds (27.5 ± 3.5 seconds).

Studies using whole-body EMS applied an on-time of 4.6 ± 1 seconds per contraction (41,69) to enhance isom *F*max (<10%). For increasing dyn *F*max (<15%) studies applied an on-time of 4.9 ± 1.7 seconds per contraction (12,13,15). Whole-body combination methods showed significant gains in dyn *F*max <10% by a use of an on-time of 7.5 ± 0.9 seconds (14,69).

In contrast, for significantly developing speed strength (RFD; force impulse) and power (including *v*max) Speicher et al. (69) applied an on-time of 60 ± 0 seconds per contraction (50% duty cycle). However, theses results have to be stated with caution because only few international studies are published in this section.

In summary, on the basis of the results independent of the local EMS method short impulse on-times (contraction time) in a range of 3–10 seconds combined with a duty cycle of 20–25% showed positive effects for enhancing maximal strength, speed strength, and jumping and sprinting ability. Whole-body EMS methods revealed that an on-time of 60 seconds with a 50% duty cycle can be effective for developing parameters of speed strength (RFD/force impulse) and power.

For regeneration time (impulse interval), the analysis showed evidence that a stimulation ratio of 20–25% duty cycle is adequate for recovery between the contractions and thus positively influences strength adaptation.

DISCUSSION

On the basis of the results, we conclude that a stimulation intensity of ≥50% MVC is required to produce a stimulus in the muscles that has sufficient intensity to activate strength adaptations. Further, the analysis revealed that the %MVC level is mainly influenced by the impulse intensity (mA), the stimulation frequency (Hz), and the impulse width (microseconds). According to this, we conclude that independent of the EMS method, an impulse intensity of ≥50 mA in connection with a stimulation frequency of 76.4 ± 20.9 Hz and an impulse width of 306.9 ± 105.1 microseconds positively influence the generation of a stimulation intensity of ≥50% MVC and thus generate a stimulus above a training threshold that activates strength adaptations. In regard to the training regimen when applying this combination of stimulation parameters, we conclude that a stimulation period in a range of 4–6 weeks with 3 sessions per week (10–15 minutes per session) and a stimulation ratio in a range of 3–10 seconds on-time (20–25% duty cycle) are sufficient for enhancing maximal strength, speed strength, jumping and sprinting ability, and power in trained and elite athletes.

Regarding training regimens, the analysis revealed that in trained subjects and elite athletes, 3 sessions per week over a stimulation period of 4–6 weeks are adequate for activating strength adaptations. In regard to maximal strength, some studies showed significant gains even after a 3-week period (cf. (20,43,54)). In contrast, speed strength, and jumping and sprinting ability show a higher complexity in movement and are therefore influenced by several parameters such as coordination and neural activation. In regard to the results, these parameters can show delays in adaptation. In keeping with this, the analysis showed that a stimulation period of ≥4 weeks (3 sessions per week) is sufficient to also ensure enhancements in speed strength and jumping and sprinting ability.

When applying an EMS stimulus according to the parameters described above independent o the EMS method used a higher number of training session (>3 sessions per week) within a stimulation period of 4–6 weeks can overstress the subject's muscular system and thus hampering strength adaptations.

According to that studies investigating the effects of EMS on creatinkinase activity showed that the electrical stimulus can cause significantly more stress in the muscular system and therefore exhibits higher creatinkinase activity compared to voluntary muscle contraction exercise (cf. (12,13,37,41)). Consequently, EMS requires a higher interval between the training sessions to not overstress the muscular system and ensure strength adaptations.

For example, Boeckh-Behrens (12) showed that, compared to traditional strength training, the stress on the muscular system is about 40% higher after intensive EMS. Boeckh-Behrens came to the conclusion that the level of stimulation intensity is responsible for the level of creatinkinase activity, whereas stimulation duration has no influence (cf. (13)).

Regarding the development of creatinkinase activity, Boeckh-Behrens documented results showing that the subjects still exhibited high values after long periods ranging from 24 hours to 4 days. Further stimulation within this time of decomposition would result in a summation of creatinkinase activity (72), which in turn can overstress the athletes' muscular system. Consequently, the size of the interval between 2 EMS sessions is very important for activating strength adaptations. According to Kreuzer et al. (41), the muscular system acclimatizes to the electrical stimulus in as little as 3 weeks, which in turn results in reduced creatinkinase activity. For example, introducing the electrical stimulus to the subjects before starting with the actual stimulation period (acclimatization period) might prevent extreme summation of creatinkinase activity and muscle soreness.

Regarding the creatinkinase activity related to the individual level of fitness, the studies analyzed in this review could not show a difference between untrained subjects and trained athletes. Steinacker et al. (72) assume that elite athletes show less creatinkinase activity compared to untrained subjects after EMS, because they have more experience in performance training and therefore a greater tolerance to highly intensive training. This would indicate that elite athletes can be stimulated with higher intensity and or with a higher number of training sessions per week.

As mentioned above, the stimulation intensity influences the level of creatinkinase activity. Accordingly, we suggest that the stimulation intensity is an important parameter for planning strength training. In contrast to voluntary exercise, with EMS, the intensity is defined by the level (%) of MVC. As shown in this review, significant enhancements in maximal strength, speed strength, and motor abilities such as jumping and sprinting have been demonstrated in connection with stimulation intensities of ≥50% MVC in combination with the training regimens described above.

Regarding the stimulation intensity, the analysis showed that intensities of ≥50% MVC were mostly produced with biphasic impulses (e.g., (6,31,37,49)). Monophasic current flows from one electrode to the other in a fixed direction that can create an ionic current within the tissue. This can result in unpleasant side effects such as electrolysis and risk of chemical burning. On the contrary, biphasic currents flow between both electrodes and thus have a zero net current (44). Accordingly, biphasic currents are perceived as more pleasant for the subjects' muscles (3,16). For this reason, subjects are able to tolerate biphasic currents better, which means that the impulses can be more intensive. Consequently, biphasic currents offer advantages for applying high stimulation intensities and therefore have a positive influence on the enhancement of strength abilities.

Regarding the stimulation parameters, the present analysis revealed that the frequency, intensity, and width of the impulses used are the most relevant stimulation parameters that influence stimulation intensity. Therefore, these parameters must be taken into consideration to generate a stimulus that activates strength adaptations.

In regard to the influence of the impulse intensity (mA) on stimulation intensity (MVC) Lake (44) was able to show in his study that the muscle contraction force can be regulated by varying the level of amperage (mA). Accordingly, a higher impulse intensity (mA) results in a higher %MVC. However, the impulse intensity depends on the resistance of different tissue structures. According to Bossert et al. (16), a major portion of the resistance is because of the resistance of the skin. Therefore, it is not possible to precisely determine the impulse intensity (mA) that ultimately reaches the muscle. Most studies used the maximum pain threshold (maximum tolerated amperage) to regulate the maximum impulse intensity (e.g. (19,31,38,41,46)). Nonetheless, the pain threshold depends on the subject's individual pain perception and on the particular muscle. Studies showed that the subjects quickly experience pain acclimatization through EMS. Accordingly, to maintain a certain level of stimulation intensity the impulse intensity (mA) has to be continuously enhanced to adapt to the changing situation (cf., e.g., (46,50)). However, Cabric and Appell (21) mentioned that when increasing the impulse intensity a maximal level of muscle contraction force is achieved with intensities over 100 mA, and no further positive effects might appear. Furthermore, maximal impulse intensities and thus a high level of muscle tension will limit dynamic movements. Therefore, in dynamic EMS methods, the impulse intensity (mA) has to be regulated to ensure unlimited movement.

Depending on the muscle structure, the amperage (mA) required to penetrate the skin (44) can vary. Consequently, trained subjects with a lower percentage of fat revealed a lower pain threshold compared to untrained subjects. This is because muscular systems with less fat offer lower resistance, which results in a higher intensity within the muscle. Furthermore, because the amperage (mA) is defined by the load that flows though a cross section of a lead per time unit (16), impulse intensity also depends on the specific area of application. Consequently, the size of the EMS electrodes influences impulse intensity within the muscle.

The analysis showed that high MVC levels (and consequently significant strength gains) were predominately achieved with an impulse intensity of $\geq$50 mA. However, research revealed that the impulse intensity is highly influenced by the individuals' pain perception, by the condition of the muscular system and by motivation (cf. (16)). In connection with the findings described above we conclude that the value of amperage is difficult to quantify, and therefore, it is rather a guide value than a decisive factor for training control.

In regard to the stimulation frequency, research in EMS showed that different stimulation frequencies activate different types of muscle fiber (4). For example, in a fiber spectrum of 2–15 Hz, mostly slow-twitch fibers (type 1) will be stimulated. According to Appell (4), Fast-twitch fibers (type 2), which are responsible for the development of high forces, may not contract below 35 Hz. A further increase in frequency then leads to a complete tetanus of the stimulated muscle. Appell (4) acts on the assumption that this maximal muscle activation can be enhanced up to a frequency of 70 Hz. According to Blümel (11), however, a complete tetanus will be reached between a frequency of 50 and 200 Hz, whereas Bossert et al. (16) came to a different conclusion; they assert that maximum stimulation for type-2 fibers takes place at around 50–60 Hz. There are different opinions about the level of stimulation frequency in the current state of research. Although Kramer (40) achieved the highest Mmax with 20 Hz, Cometti (23) recommends impulse frequencies from 50 to 100 Hz. Binder-Macleod and Guerin (9) came to a similar result. They see higher frequencies between 60 and 100 Hz as more effective.

In regard to the results of this review in connection with the findings described above, we conclude that impulse frequencies in a range between 50 and 100 Hz are sufficient for generating high stimulation intensities (MVC) when applied in combination with an adequate impulse intensity and impulse width.

The minimal impulse width is defined by the minimal time required (chronaxie) for the swell intensity to create an action potential within the stimulated motor neuron. According to Bossert et al. (16), this impulse width lies in the range of 80–800 microseconds. Longer impulse durations (wider impulses) result in proportionately deeper and more intensive muscle stimulation (cf. (7,16)) and thus more motor units will be recruited. However, the presence of algesic substances increases as the width rises.

Hultmann et al. (36) have held that a minimum impulse width of 500 microseconds is needed to develop high forces. Their results show that lowering the impulse width significantly reduces the MVC produced. Bossert et al. (16) came to the conclusion that no widths above 500 microseconds should be used, because impulses above this level would be unpleasant or even painful. They assume that no sensitive reactions are to be expected on a level around 300 microseconds. For this reason, they recommend a level between 300 and 400 microseconds.

In connection with the results of this review, we conclude as a compromise that an impulse width in a range between 200 and 400 microseconds is sufficient for generating high stimulation intensities $\geq$50% MVC. Furthermore, the application will also activate the deeper motor units without being unpleasant for the athlete, but the stimulus will be intensive enough to cause strength adaptations.

Regarding the stimulation ratio, the analysis revealed a predominant use of short impulse on-times of 6.0 ± 2.4 seconds in all EMS methods for enhancing strength abilities.

In voluntary exercise the stimulation ratio is used to specify the training program in relation to certain strength abilities. According to Weineck (74), in traditional strength training, speed strength, and maximal strength will be trained using impulse on-times (contraction time) between 3 and 6 seconds per contractions, whereas muscle hypertrophy will be activated after 10 seconds of duration. In particular, maximal strength and speed strength are both influenced by coordination and neuronal activation. The analysis revealed that with EMS the strength abilities are mainly increased by neuronal adaptations and less through hypertrophy. For example, the increase in power went in hand with an increase in $v$max, which again is influenced by several neuronal factors such as coordination and neuronal activation (69). Accordingly, in regard to the results of this review, we can state that short impulse on-times also positively influence the enhancement in maximal strength and speed strength with EMS.

Regarding the interval between 2 single impulses, Appell (3) sees the off-phase as regeneration time for recovering energy depots and for restitution of the motor end plate. He assumes that a ratio between 1:1 and 1:5 is optimal. According to Edel (27), intervals that are too short cause the muscles to fatigue rapidly, which reduce the effect of training.

In summary, we conclude that the use of short impulse on-times (contraction time) between 3 and 10 seconds positively influence the enhancement of maximal strength and speed strength and thus jumping and sprinting ability and power. For regeneration time (impulse interval) we assume that a stimulation ratio with a 20–25% duty cycle and a short duration of 3–10 seconds ensures sufficient recovery and thus enables strength adaptations.

Regarding the enhancements gained for the analyzed strength parameters that were shown in the first study (cf. (30)) in relation to training regimen and stimulation parameters, this study demonstrated that untrained subjects are able to significantly enhance all strength parameters within 3–6 weeks with a wide variety in training patterns, whereas elite athletes only have small improvement reserves.

As mentioned before, EMS is an intensive training method that can require a higher interval between sessions than voluntary exercise. Accordingly, EMS has to be applied with caution. Especially untrained subjects have to be trained with caution because of their lower resistance to intensive load. Overloading the subjects' muscular system by for example applying EMS with a high stimulation intensity in combination with not enough regeneration time between the sessions can inhibit or delay strength adaptations. Consequently, significant strength gains were often first demonstrated in retesting after a rehabilitation (detrain) period of 2–6 weeks (cf. (32,41,46,49,69)). Employing a load that was too low, on the other hand, resulted in a rapid decrease (within 2–4 weeks) in achieved strength gains after posttesting (cf. (32,43,53)), or led to a lack of any significant enhancements in posttesting (17,24,33,41,52,55,58,61,65,68,69,71).

In contrary, several trials revealed that, when EMS was applied with optimal load, the achieved strength gains can be kept at a constant level in untrained and trained subjects for up to 4 weeks after posttesting without doing any exercise (cf. (7,17,32,38,41,43,60,69)). In the case of elite athletes, the analysis showed that continuing the usual high-performance training after posttesting can keep or even enhance the achieved strength gains for up to 6 weeks (46,47,50). In keeping with this, for example, Maffiuletti et al. (56,57) showed further strength increases in the vertical jump height of elite basketball players (+3% SJ, +17% CMJ) and elite volleyball players (+1.6% SJ, +5% CMJ, ±0% DJ) within 6 weeks after posttesting. On the basis of these results, we can assume that athletic training or strength training after finishing the stimulation period is able to maintain the achieved levels of strength and jumping ability.

Regarding changes in strength gains after posttest the analyzed data suggest a relationship between stimulation intensity and the period over which it is possible to maintain the achieved gains. Furthermore, the changes in strength after posttesting (detraining) showed that gains achieved over longer periods (4 weeks) are more likely to remain constant after posttesting (7). As seen in traditional training, also in EMS training gains achieved in a short period of time (<4 weeks) decreased more quickly after posttesting (43).

PRACTICAL APPLICATIONS

The following guidelines for strength training control were developed because of the results of this review series and include recommendations for developing maximal strength and speed strength and jumping and sprinting ability, and power in strength training especially in high-performance sports.

The present analysis revealed that a stimulation intensity of ≥50% MVC in connection with the training regimen in the recommended range (4–6 weeks, 3 sessions per week) is a precondition for activating strength adaptations. To generate a stimulus above training threshold, coaches should apply an impulse width in a range of 200–400 microseconds and an impulse frequency of 50–100 Hz. For regulating the impulse intensity and thus generating an adequate level of stimulation intensity (%MVC), trained and elite athletes should approach a submaximal to maximum level of mA (≥50 mA).

Before applying EMS with this intensity (≥50% MVC), EMS training intensity should be increased step by step. This helps to accommodate individual reactions to the EMS stimulus, athletes will be introduced to it before starting the actual stimulation period, and coaches can set the training level of impulse intensity (mA) according to the individual's maximum tolerated level more easily without risking overstressing the subjects' muscular system. When this is done, the subjects are able to get used to the electrical stimulus that is significantly more intensive compared to voluntary contraction stimulus in traditional weight training which can cause significantly higher damage in the athletes' muscular system. Furthermore, this will reduce muscle soreness in the beginning.

When setting the stimulation intensity for training, compared to trained subjects and elite athletes, untrained subjects should not focus on the maximum tolerated impulse intensity (mA) in order not to overstress the muscular system. For acclimatization, we recommend to start with 1 session per week. Within the actual stimulation period, untrained subjects should train a maximum of 2 times a week with a submaximal intensity. Trained subjects and elite athletes should start with 2 sessions per week with submaximal intensity before applying EMS with individual maximum intensity within the actual training period. In general, regardless of their level of fitness, subjects should not exceed 3 sessions per week (including additional voluntary strength training).

The stimulation intensity (%MVC) is influenced by the level of impulse intensity (mA) and depends on individual perception and structure of the muscle. To maintain the level of MVC during the training period and thus ensure strength adaptations, the impulse intensity (mA) has to be carefully and constantly enhanced to account for acclimatization. The impulse frequency, impulse width, impulse type, and stimulation ratio should stay on the defined level during training period (4–6 weeks).

To maintain the achieved strength gains, athletes should integrate a specific strength training (maximal strength, speed strength) or athletic training (sprinting, jumping, coordination) into their daily training (minimum 1 sessions per week) after finishing the simulation period. If continuing with EMS training, a variation of stimulation parameters alters the training stimulus and can thus show positive effects on maintaining or even further enhance the achieved strength gains.

Although the first study revealed the effectiveness of EMS, EMS should be used as an additional training alternative in strength training and not as a complete replacement. Regardless of the EMS method used, additional athletic performance training has a positive influence for transferring the strength gains to specific types of movements, such as sprinting or jumping.

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