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MINI REVIEW

Is high-frequency neuromuscular electrical stimulation a suitable tool for muscle performance improvement in both healthy humans and athletes?

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Abstract We aimed at providing an overview of the currently acknowledged benefits and limitations of neuromuscular electrical stimulation (NMES) training programs in both healthy individuals and in recreational and competitive athletes regarding muscle performance. Typical NMES resistance exercises are performed under isometric conditions and involve the application of electrical stimuli delivered as intermittent high frequencies trains (>40–50 Hz) through surface electrodes. NMES has been acknowledged as an efficient modality leading to significant improvements in isometric maximal voluntary strength. However, the resulting changes in dynamic strength, motor performance skills and explosive movements (i.e., jump performance, sprint ability) are still ambiguous and could only be obtained when NMES is combined with voluntary dynamic exercise such as plyometrics. Additionally, the effects of NMES on muscle fatigability are still poorly understood and required further investigations. While NMES effectiveness could be partially related to several external adjustable factors such as training intensity, current characteristics (e.g., intensity, pulse duration…) or the design of training protocols (number of contractions per session, number of sessions per week…), anatomical specificities (e.g., morphological organization of the axonal branches within the muscle) appear as the main factor accounting for the differences in NMES response. Overall, NMES cannot be considered as a surrogate training method, but rather as an adjunct to voluntary resistance training. The combination of these two training modalities should optimally improve muscle function.

Keywords Skeletal muscle · Strength gains · Resistance training · Muscle function

Introduction

The utilization of electrical current as a potential trigger of muscle contraction has been reported ~350 years ago. In the 1670s, Jan Swammerdam (1637–1680) established that a frog nerve–muscle preparation could be externally stimulated (“irritated”) through the nerve with scissors (Cobb 2002) but did not manage, at that time, to explain the detailed mechanism leading to muscle activation. In 1747, Jean Jallabert (1712–1768) managed to chronically stimulate the paralyzed right upper limb of a patient using electrical stimulation from a Leyden jar (in other words a battery), thereby improving his muscle function after a 3-month treatment period. In 1791, when Luigi Galvani (1737–1798) was dissecting out a frog on a bench, while conducting experiments with static electricity, his assistant touched by chance an exposed sciatic nerve with a metal scalpel which had picked up a charge and they immediately saw sparks and a resulting strong muscle contraction of the frog’s leg. At this stage, although the physiological mechanisms underlying muscle activation were initially misunderstood and strongly debated with Alessandro Volta, Galvani’s fundamental finding was that electrical current can evoke muscle contraction. The discovery of

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electromagnetic induction by Michael Faraday (1791–1867) led to the development of modern electrical generators and was of crucial importance. Guillaume Duchenne de Boulogne (1806–1875), considered as the pioneer of electrotherapy (Reincke and Nelson 1990), was one of the first to use faradic currents in order to stimulate facial muscles with moistened surface electrodes. Combining photography and electrical stimulation, he elegantly described the relationship between facial muscular contraction and the corresponding expressed emotion.

Given the large number of war-related injuries which occurred during the first half of the twentieth century, electrical stimulation emerged as a suitable tool for counteracting muscle atrophy resulting from denervation (Jackson and Seddon 1945; Osborne 1951). In 1971, the Russian researcher Yakov Kots claimed that muscle electrical stimulation might be more efficient than voluntary contractions in order to increase maximal strength (Ward and Shkuratova 2002). Considering the well-known Olympic motto "Faster, Higher, Stronger", the remarkable Kots' findings laid the foundation for the use of electrical stimulation as a modality of muscle performance improvement. However, given the poorly controlled utilization, this artificial training method has been initially considered as a technological gadget rather than as a suitable tool for increasing muscle strength. There are now compelling evidence that electrical stimulation is a relevant and legal complement (e.g., as compared to doping procedure) to voluntary resistance training protocols for muscle strength improvement.

In the present review, we defined neuromuscular electrical stimulation (NMES) as the application of electrical stimuli delivered as intermittent high frequencies trains (>40–50 Hz) through surface electrodes positioned over the motor-point in order to produce (strong) skeletal muscle contractions as a result of intramuscular nerve branches' activation (Hultman et al. 1983). We aimed at providing an overview of the current knowledge related to changes in muscle performance resulting from multiple bouts of NMES in both healthy humans and in recreational and competitive athletes. More particularly, we have addressed the issues related to the benefits and limitations of NMES training. Underlying mechanisms accounting for strength improvement and aspects of NMES physiology (e.g., motor unit recruitment) are beyond the scope of the present review and have been discussed in recent reviews (Maffiuletti 2010; Vanderthommen and Duchateau 2007).

We chose to perform an open ended review given that more stringent methods could have resulted in too many important articles being discarded (Bax et al. 2005). The computerized literature search was performed within the Pubmed database using the following combination of keywords ["electrical stimulation" [or] "neuromuscular electrical stimulation" [or] "electromyostimulation" [or] "electrostimulation"] and ["training" or "resistance training" or "strength training"] and ["humans" or "athletes" or "sporstmen"]. We selected articles published up to December 2010 and involving young healthy humans/athletes (~18–35 years). We also chose to select articles for which changes in muscle performance resulting from NMES have been evaluated on the basis of various outcome parameters including maximal voluntary strength (isometric and/or dynamic), jump performance, sprint ability and muscle fatigability. Studies conducted in animal models, in patients unable to follow conventional rehabilitation programs (see Kim et al. 2010; Monaghan et al. 2010; Sillen et al. 2009; Vivodtzev et al. 2008 for reviews) and combining NMES with dietary supplementation have been excluded. Additionally, previous review articles (Hainaut and Duchateau 1992; Kramer and Mendryk 1982; Lake 1992; Lloyd et al. 1986; Requena Sanchez et al. 2005; Singer et al. 1987; Vanderthommen and Duchateau 2007) were selected in order to identify additional articles that may contain information of interest.

NMES efficiency in healthy humans

Effects on isometric strength

NMES training has been applied in various muscles including the *triceps surae* (Martin et al. 1993), *biceps brachii* (Colson et al. 2000), *triceps brachii* (Rich 1992), *adductor pollicis* (Duchateau and Hainaut 1988), *first dorsal interosseus* (Davies et al. 1985), *abductor digiti quinti* (Goonan et al. 1985), *harmstrings* (Porcari et al. 2002), *abdominals* (Alon et al. 1992) and *quadriceps* (Currier and Mann 1983), the latter being the most often stimulated muscle (Bax et al. 2005). It has been largely acknowledged that NMES is a relevant tool resulting in an increased maximal isometric voluntary strength (Boutelle et al. 1985; Colson et al. 2000, 2009; Currier and Mann 1983; Duchateau and Hainaut 1988; Fahey et al. 1985; Gondin et al. 2005, 2006a; Halback and Straus 1980; Kubiak et al. 1987; Laughman et al. 1983; Maffiuletti et al. 2002b; McMiken et al. 1983; Parker et al. 2003; Romero et al. 1982; Selkowitz 1985; Soo et al. 1988; Stefanovska and Vodovnik 1985; Zhou et al. 2002) even though anecdotal and poorly controlled studies (Mohr et al. 1985; Owens and Malone 1983; Rich 1992) have failed to report similar beneficial effects. It is noteworthy that the improvement extent of isometric force widely differed among studies ranging from 9 (Herrero et al. 2006) to 48% (Lai et al. 1988) in the *quadriceps* muscle (Table 1). It has also been reported that isometric strength was higher than baseline values 3–4 weeks after the cessation of NMES training (also referred to as detraining) (Boutelle et al. 1985; Gondin et al. 2006b; Lai et al. 1988). Additional work would be warranted in order to determine whether this NMES-induced strength gain could last longer than 4 weeks. Interestingly, Zory et al. (2010) failed to report strength enhancement after a short-term NMES training protocol resulting in alterations of contractile properties. However, after a 4-week detraining period, they observed a delayed strength improvement occurring simultaneously to the normalization of the contractile function thereby illustrating that the beneficial effects of NMES might be delayed. A short-term NMES program has also been associated to an improved isometric strength of both the untrained (or contralateral) and trained limbs with a lower improvement for the untrained limb (Hortobagyi et al. 1999; Lai et al. 1988; Laughman et al. 1983; Zhou et al. 2002). This phenomenon, referred to as cross-education, would apply for isometric strength only, given that no dynamic strength change was measured. Despite all these beneficial effects related to an increased isometric voluntary strength, it should be kept in mind that NMES alone or combined to voluntary contractions is less or equally effective than voluntary exercise modality (see Bax et al. 2005; Paillard et al. 2005 for reviews). The higher strength gains reported after voluntary resistance training as compared to those induced by NMES could be related to the higher training intensity that was often maximal during volitional contractions as compared to the submaximal intensity reached during NMES (Table 1).

Effects on dynamic strength and explosive movements

On the contrary to what has been observed for isometric strength, dynamic strength enhancement following NMES training in non-athlete subjects is still debated since maximal concentric strength was found to be unchanged (Boutelle et al. 1985; Currier and Mann 1983; Kubiak et al. 1987; Maffiuletti et al. 2002b; St Pierre et al. 1986) or increased either for specific (mainly low) angular velocities (Colson et al. 2000, 2009; Nobbs and Rhodes 1986; Romero et al. 1982) or for all (tested) (Bircan et al. 2002; Fahey et al. 1985; Halback and Straus 1980; Martin et al. 1993; Zhou et al. 2002) angular velocities (Table 1). Information regarding NMES-induced changes in maximal eccentric strength are scarce and ambiguous with studies reporting either beneficial effects for *elbow flexor* (Colson et al. 2000, 2009) and *plantar flexor* muscles (Maffiuletti et al. 2002b) or no improvement for the quadriceps muscle (Lai et al. 1988).

Similarly, only a few studies (Eriksson et al. 1981; Herrero et al. 2006; Paillard et al. 2008; Venable et al. 1991) have assessed changes in motor performance skills or explosive movements following multiple bouts of NMES and the results are also equivocal. Indeed, Herrero et al. (2006) reported that NMES did not result in any improvement in jump explosive strength or even interfere with sprint run while three studies (Eriksson et al. 1981; Paillard et al. 2008; Venable et al. 1991) demonstrated that NMES alone or combined with voluntary contractions slightly enhanced jump performance. Overall, the lack of (or small) improvement in dynamic performance following NMES is highly consistent with the well-known concept of “training mode-dependence” typically observed after voluntary resistance programs. This concept is related to the fact that improvement of muscle performance has been mainly reported when testing procedures were similar or close to the training mode used (Thepaut-Mathieu et al. 1988). Given that NMES training is mainly delivered under isometric conditions, strength improvement is, therefore, limited to both isometric and slow dynamic actions and is larger for joint angle close to the training position (Maffiuletti et al. 2002b; Martin et al. 1993). Taken together, these results illustrate that NMES cannot be considered as a surrogate training method but rather as an adjunct to voluntary resistance training and that these two training modalities should be combined in order to optimally improve muscle capacity.

Effects on muscle fatigue

Although it is commonly accepted that the peculiar motor unit recruitment associated with NMES (Gregory and Bickel 2005) would be linked to an exaggerated metabolic demand (Vanderthommen et al. 2003) which could hasten the onset of muscle fatigue (Jubeau et al. 2008; Theurel et al. 2007), the effects of multiple NMES sessions on muscle fatigue have been scarcely investigated and the results are still ambiguous. For example, Duchateau and Hainaut (1988) reported that the decline in evoked force during an intermittent electrical fatigue task was similar before and after a 6-week NMES training session. Similarly, the maximal voluntary contraction (MVC) torque decline recorded at exhaustion after a submaximal isometric fatiguing contraction of the *knee extensor* muscles was not affected by multiple bouts of NMES (Gondin et al. 2006c). Additionally, muscle endurance of the abdominal and quadriceps muscles was unchanged following 4–5 weeks of NMES training (Alon et al. 1987; Eriksson et al. 1981). On the contrary, Porcari et al. (2002) reported a 100% increase in abdominal endurance as a result of an 8-week NMES training period. However, they also reported an improved endurance in subjects who were not engaged in the stimulation program. It has also been reported that a 4- to 6-week NMES training period led to an increased endurance time for a cycling exercise or dynamic knee extension at 50% MVC but did not affect maximal

Table 1 Effects of NMES training alone or combined with voluntary resistance training on isometric and/or dynamic strength of the quadriceps muscle

Authors	Sample size/ sex	Current type	Pulse shape	Pulse wide (ms)	Frequency (Hz)	Training intensity (%MVC)	On-Off time (s)	Session duration (min)	Training (Weeks/sessions)		Training mode	Testing velocities (°/sec)	Strength gains (%)	Conclusions
Balogun et al. (1993)	10m 10m 10m	Pulsed Pulsed Pulsed	M TP M TP M TP	~0.07 ~0.07 ~0.07	20 45 80	N/A N/A N/A	10/50 10/50 10/50	10 10 10	6 6 6	18 18 18	NMES NMES NMES	0	24% (mean of the three groups)	No effect of pulse frequency on strength gains
Gondin et al. (2005)	12m 8m	Pulsed –	R B –	0.4 –	75 –	68 –	6/20 –	17.5 –	8 –	32 –	NMES @ 60° CONT	0 0	27 NS	NMES > CONT
Herrero et al. (2006)	10m 9m 10m 11m	Pulsed – – Pulsed	B S SQ – – B S SQ	0.4 – – 0.4	120 – – 120	N/A – – N/A	3/30 – – 3/30	29 25 – 25 and 29	4 4 – 4	16 8 – 8 and 8	NMES @ 60° Plyo CONT NMES @ 60° & Plyo	0	9 NS NS 16	NMES = NMES & Plyo > Plyo = CONT
Herrero et al. (2010a)	10m 8m 10m	– – Pulsed	– – B S SQ	– – 0.4	– – 120	70 – 70	2/1 – 2/1	25 – 25	4 – 4	16 – 16	VOL @ 90°/s CONT NMES + VOL @ 90°/s	0	31 NS 40	NMES + VOL = VOL > CONT
Herrero et al. (2010b)	11m 8m 10m	– – Pulsed	– – B S SQ	– – 0.4	– – 120	70 – 70	2/1 – 2/1	25 – 25	4 – 4	8 and 8 – 8 and 8	VOL & Plyo CONT (NMES + VOL @ 90°/s) & Plyo	0	22 NS 29	(NMES + VOL @ 90°/s) & Plyo > VOL & Plyo > CONT
Laughman et al. (1983)	20m/f 19m/f 19m/f	Alt – –	SIN – –	N/A – –	2,500mo50 – –	33 78 –	10/50 10/50 –	10 10 –	5 5 –	25 25 –	NMES @ 60° VOL @ 60° CONT	0	22 18 NS	NMES = VOL > CONT
McMiken et al. (1983)	2m/8f 1m/7f	Alt –	N/A –	0.1 –	75 –	80 ~100	10/50 10/50	10 10	3 3	10 10	NMES @ 30° VOL @ 30°	0	22 25	NMES = VOL
Mohr et al. (1985)	6f 5f 6f	Galv – –	TP – –	0.03 – –	50 – –	N/A 100 –	10/10 10/10 –	3.3 3.3 –	3 3 –	15 15 –	NMES @ 60° VOL @ 60° CONT	0	NS 15 NS	VOL > NMES = CONT
Owens and Malone (1983)	9m/6f	Alt Alt –	SIN SIN –	0.2 0.2 –	2,500mo50 2,500mo50 –	60 39 –	15/50 15/50 –	10.8 10.8 –	1.4 1.4 –	10 10 –	NMES @ 35° NMES @ 35° CONT	0	NS NS NS	No significant strength gains
Parker et al. (2003)	2m/7f 3m/6f 2m/7f	Alt Alt –	SIN SIN –	0.2 0.2 –	5,000mo50 5,000mo50 –	69 63 –	10/50 10/50 –	10 10 –	4 4 –	12 8 –	NMES @ 60° NMES @ 60° CONT	0	12.5 NS NS	NMES 3 times a week > NMES 2 times a week = CONT
Selkowitz (1985)	4m/8f 4m/8f	Alt –	SIN –	0.45 –	2,200mo50 –	91 –	10/120 –	21.7 –	4 –	12 –	NMES @ 60° CONT	0	44 18	NMES > CONT No sex difference
Soo et al. (1988)	9m 6f	Alt Alt	SIN SIN	N/A N/A	2,500mo50 2,500mo50	50 50	15/N/A 15/N/A	2 2	5 5	10 10	NMES @ 60° NMES @ 60°	0	24 NS	Strength gains only in men Sex difference ➔ small sample size?
Boutelle et al. (1985)	7m/2f 3m/5f	Alt –	SIN –	0.2 –	2,500mo50 –	N/A –	10/50 –	10 –	4 –	20 –	NMES @ 30° CONT	0/+60/+240	32/NS/NS NS/NS/NS	NMES > CONT
Currier and Mann (1983)	5m/4f 4m/4f 5m/3f 5m/4f	– – Alt Alt	– – SIN SIN	– – 0.1 0.1	– – 2,500mo50 2,500mo50	– 100 60 100	– 15/50 15/50 15/50	– 10.8 10.8 10.8	– 3 3 3	– 15 15 15	CONT VOL @ 60° NMES @ 60° NMES @ 60°+ VOL	0/+100/ +200/+300	NS/NS/NS/NS 30/NS/NS/NS 17/NS/NS/NS 23/NS/NS/NS	VOL = NMES = VOL + NMES >> CONT No effect on dynamic strength
Erikkson et al. (1981)	9m 4m 4m	N/A N/A –	SQ SQ –	0.5 0.5 –	50 50 –	N/A N/A 100	15/15 6/6 6/6	6 3.6 3.6	5 4 4	20–25 15 15	NMES @ 90° NMES @ 90° VOL @ 15°/s	0 0/+15/+30/+60/ +90/+180	18 14/16/13/10/13/14 16/22/27/17/10/9	NMES = VOL
Fahey et al. (1985)	9m/9f 10m/9f 9m/9f	Pulsed Pulsed –	A B SQ –	N/A N/A –	50 50 –	N/A N/A –	10/5 10/5 –	15 15 –	6 6 –	18 18 –	NMES @ 65° NMES @ 0° CONT	0/+30/+60/+90/ +120	12/13/9/7/8 10/7/6/4/2 NS/NS/NS/NS	NMES @ 65°> NMES@ 0° > CONT No sex difference
Hortobagyi et al. (1999)	8f 8f 6f	Alt – –	SIN – –	N/A – –	2,500mo50 – –	N/A – –	N/A N/A –	~6 ~6 –	6 6 –	24 24 –	NMES @ –60°/s VOL @ –60°/s CONT	0/–60	22/36 25/54 NS	NMES = VOL > CONT
Kubiak et al. (1987)	9m/f 10m/f 10m/f	– – N/A	– – N/A	– – N/A	– – « High frequency »	– 100 ~45–75	– 10/50 10/50	– 10 10	– 5 5	– 15 15	CONT VOL @ 60° NMES @ 60°	0/+60	NS/NS 43/NS 33/NS	VOL > NMES > CONT

Table 1 continued

Authors	Sample size Sex	Current type	Pulse shape	Pulse wide (ms)	Frequency (Hz)	Training intensity (%MVC)	On-Off time (s)	Session duration (min)	Training (Weeks/sessions)		Training mode	Testing velocities (°/sec)	Strength gains (%)	Conclusions
Lai et al. (1988)	4m/4f	Pulsed	B A SP	0.2	50	25	5/5	8	3	15	NMES @ 60°	0/+60/–60	24/12/NS	NMES @50%MVC > NMES @25%MVC > CONT
	4m/4f	Pulsed	B A SP	0.2	50	50	5/5	8	3	15	NMES @ 60°		48/22/NS	No effect on eccentric strength
	4m/4f	–	–	–	–	–	–	–	–	–	CONT		NS/NS/NS	
Nobbs and Rhodes (1986)	9f	Alt	R	N/A	60	N/A	10/50	10	6	18	NMES @ 45°	0/+30/+100/+180	29/11/NS/NS	NMES = NMES + VOL = VOL
	9f	Alt	R	N/A	60	100	3/3	1.8	6	18	NMES + VOL @ 30°/s		17/18/NS/NS	No effect on high speed (i.e. 100°/s) dynamic strength
	9f	–	–	–	–	100	3/3	1.8	6	18	VOL @ 30°/s		26/17/NS/NS	
Portmann and Montpetit (1991)	11f	Alt	M R	0.4	2,000mo100	85–94	10/50	10	8	24	NMES @ 90°	0/+15/+180	21/NS/27	NMES @ 90° = NMES @ 9°/sec > CONT
	11f	Alt	M R	0.4	2,000mo100	82–93	10/50	10	8	24	NMES @ 9°/sec		17/NS/27	
	11f	–	–	–	–	–	–	–	–	–	CONT		NS/NS/NS	
Romero et al. (1982)	9f	Alt	N/A	N/A	2,000	N/A	4/4	15	5	10	NMES @ 65°	0/+30/+60	DL: 21/NS/NS	NMES > CONT
	9f	–	–	–	–	–	–	–	–	–	CONT		NDL: 31/13/NS	Less effective as the speed of movement increased
													No changes in CONT	
Zhou et al. (2002)	10m	Pulsed	N/A	0.25	100	65	5/20	16.7	3	12	NMES @ 90°	0/+60/+180	21/22/16	NMES = VOL
	10m	–	–	–	–	65	5/5	14.7			VOL @ 90°		24/22/17	
	10m	–	–	–	–	–	–	–			CONT		NS/NS/NS	
Bircan et al. (2002)	5m/5f	Alt	B	N/A	2,500mo80	N/A	13/50	15	5	15	NMES @ 0°	+60/+120	14/18	NMES > CONT
	5m/5f	Pulsed	S B	0.1	80	N/A	13/50	15	5	15	NMES @ 0°		21/23	
	5m/5f	–	–	–	–	–	–	–	–	–	CONT		NS/NS	
Halbach and Straus (1980)	3 ?	Alt	M SIN	N/A	50	N/A	10/50	10	3	15	NMES @ 45°	+120	22	VOL > NMES
	3 ?	–	–	–	–	N/A	N/A	N/A	3	15	VOL @ 120°/s		42	
Hartsell (1986)	5m	–	–	–	–	–	–	–	–	–	CONT	+30	No significant difference between groups	Minimal effect on dynamic strength
	4m	–	–	–	–	100	10/50	10	6	30	VOL			
	6m	N/A	M SQ	2	65	N/A	10/50	10	6	30	NMES @~30° + VOL			
	6m	N/A	B SQ	2	65	N/A	10/50	10	6	30				
Kim et al. (1995)	7m	N/A	B SIN	0.5	50	Load= 30W	N/A	60	4	12	NMES induced leg extension on ergocycle	+30/+180/+360	NS/NS/NS	No effect on dynamic strength
St Pierre et al. (1986)	7m	Alt	SIN	N/A	2,500mo50	80–100	10/50	10	1.1	7	NMES @ 90°	+24/+126	−17/NS	NMES may decrease dynamic strength
	3f	Alt	SIN	N/A	2,500mo50	80–100	10/50	10	1.1	7	NMES @ 90°		NS/NS	

Data presented in this table were obtained from the trained limbs of young healthy humans (~18–35 years) immediately after training. For the sake of clarity, data obtained after a detraining period and/or on the untrained limbs were not included. Studies were organized in alphabetical order and differentiated according to the outcome parameters, i.e., isometric strength only (light gray), combination of both isometric and dynamic strength (white) and dynamic strength only (dark gray)

For all angles, 0° corresponds to the full extension of the knee. Underlined results were calculated from original data reported in tables of the corresponding studies

Null, positive and negative testing velocities correspond to isometric, shortening and lengthening contractions, respectively

NMES @ 60° indicates that NMES training was performed with the knee flexed at 60°; NMES @ 15°/s indicate that NMES training was performed with muscle shortened at 15°/s; NMES @ −60°/s indicate that NMES training was performed with muscle lengthened at 60°/s

NMES + VOL training indicated that NMES was superimposed to voluntary contractions; NMES & VOL training indicated that both training modalities were performed separately

A asymmetric, *Alt* alternating, *B* biphasic, *CONT* control, *DL* dominant leg, *f* female, *Galv* galvanic, *m* male, *M* monophasic, *N/A* not available, *NDL* non-dominant leg, *NMES* neuromuscular electrical stimulation training, *NS* not significant, *Plyo* plyometric training, *R* Rectangular, *S* symmetric, *SIN* sinusoidal, SP spike, SQ square, *TP* twin peak, *2,500mo50* alternating current was delivered at a frequency of 2,500 Hz modulated at 50 burst per second, *VOL* voluntary training

voluntary strength (Hartsell 1986; Kim et al. 1995). Jubeau et al. (2007b) also reported a reduced muscle fatigue associated with a NMES fatiguing task. This reduction was delayed (4 weeks) with respect to the termination of the training session thereby underlying the need for a detraining period in order to benefit from the NMES training in terms of muscle fatigue. However, it is noteworthy that this beneficial effect was mainly related to a reduced activation failure due to subject's accommodation to pain or discomfort during the NMES exercise. It remains to be demonstrated whether (and how) these adaptations might be beneficial for more complex tasks such as aerobic exercise. Interestingly, we have recently demonstrated that NMES training led to a significant improvement in oxidative capacity and a shift toward a slower muscle phenotype (Gondin et al. 2011) so that further studies would be warranted in order to assess the potential usefulness of NMES in terms of muscle resistance to fatigue.

NMES efficiency in athletes

The rationale behind the utilization of NMES in sportsmen is based on the peculiar motor unit recruitment pattern associated with NMES. Indeed, during NMES, fast-twitch muscle fibers can be activated at low-force level, whereas these fibers are usually recruited for high levels of muscle strength and power during voluntary actions (Gregory and Bickel 2005; Jubeau et al. 2007a). Growing evidence is emerging illustrating the potential beneficial effects of a short-term NMES training program in both recreational and athletes engaged in individual (swimming, tennis, weightlifting…) and team sport activities (basketball, volleyball, ice hockey, rugby…). As mentioned in the "Introduction", the Russian researcher Yakov Kots was the first to introduce NMES as a modality for muscle strengthening and claimed that NMES led to strength gains up to 40% in elite athletes. However, the corresponding study was poorly described and initially published in Russian until its original translation in English (Ward and Shkuratova 2002). To our knowledge, Delitto (1989) was the first to report (in English) the improved muscle performance (front squat, snatch and clean and jerk) associated with NMES training in a competitive weightlifter (Table 2). Interestingly, the subject was able to tolerate training intensity greater than 100% MVC mainly because he get used to a certain degree of discomfort associated with high-resistive weight training. As illustrated in Table 2, NMES can enhance muscle performance in athletes without interfering with sport-specific training. For instance, a 3-week NMES session has been related in swimmers to a significant improvement of isometric, dynamic voluntary strength and swimming performance (Pichon et al. 1995).

It has also been demonstrated that improvement of performance for complex movements required a period of specific training before the beneficial effects of NMES could be observed. Indeed, maximal strength and squat jump performance were increased after 4 weeks of combined NMES and standardized basketball training. An additional 4 weeks of specific training period was necessary in order to improve performance for a more complex skill such as counter movement jump (Maffiuletti et al. 2000). These delayed adaptations indicated that strength gains do not necessarily result in greater jumping ability because performance associated to complex movements such as those involving the stretch shortening cycle is primarily related to the "tuning of control" of muscle properties (e.g., neuromuscular coordination, timing or technique) (Maffiuletti et al. 2000; Malatesta et al. 2003). On that basis, it has been proposed that the combination of NMES and voluntary dynamic exercise might be helpful for accelerating the improvement in specific power. Indeed, a 4-week combined NMES and plyometric training program led to a significant improvement in both maximal strength and vertical jump performance (Maffiuletti et al. 2002a), thereby indicating that sport-specific workouts or dynamic exercises are of utmost importance in order to improve the neuromuscular performance during complex and/or specific abilities. Also, two studies demonstrated that reducing the number of NMES training session (from 3 times a week to once a week), mimicking a taper period, resulted in either strength gains preservation (Deley et al. 2011) or in a further improvement in both voluntary strength and vertical jump height (Babault et al. 2007).

Even though athletes are often unwilling to use NMES due to the pain and/or discomfort associated with stimulation, this training modality is less time consuming than voluntary resistance training protocols (i.e., 15–20 vs. 30–60 min) so that NMES appears as a method of choice when the time available for strengthening program is limited. NMES can be applied on a single (or target) muscle so that it might be of interest in order to prevent muscle injury that could be induced by heavy-weight training in very young athletes (e.g., low back pain in gymnasts) (Deley et al. 2011). This artificial training method could also be an interesting way of providing diversity and variability in training programs, which might enhance athletes' motivation. Finally, NMES could be easily incorporated into the preparatory season of competitive athletes even though further studies are needed in order to design the optimal periodicity of NMES training.

Accounting factors of NMES efficiency

The large variability associated to NMES efficiency (see Table 1) could be partially related to several external adjustable factors.

Training and current intensity

The training intensity (sometimes referred to as training dose) has been commonly defined as the ratio between the level of each electrically-evoked force and the isometric MVC force recorded before starting the NMES protocol. Conflicting findings have been initially reported regarding the influence of training intensity in the magnitude of the NMES-induced strength gains. For instance, NMES exercise performed at 33% MVC led to an 18% strength gain (Laughman et al. 1983), whereas Parker et al. (2003)

Table 2 Effects of NMES training alone or combined with voluntary resistance training on muscle performance in athletes

Authors	Sport and level	Sample size Sex	Design of training protocol									Athletic performance	
			Training modality	Frequency (Hz)	Training intensity (%MVC or RM)	Session duration (min)	Training (Weeks/sessions)		Nb of reps	Trained muscle	Mode	Recorded variables	Results
Delitto et al. (1989)	Weightlifting	1m	NMES & VOL	2,500m75	112 & N/A	∼32 & 180	6 & 14	12 & 84	10 & N/A	QF	ISO	Front squat	+20 kg
	Olympic											Snatch	∼+10 kg
												Clean & Jerk	∼+10 kg
Pichon et al. (1995)	Swimming	7m	NMES	80	60	12	3	9	27	LD	ISO	Isometric MVS	+21%
	Nat and reg											Eccentric MVS	+24%
												Concentric MVS	+10–15%
												25-m pull-boy	−0.19 sec
												50-m freestyle	−0.38 sec
												Stroke length	+0.05m cycle^{-1}
Willoughby & Simpson (1996)	Basketball	6m	NMES	2,500mo50	N/A	N/A	6	18	24–30	BB	DYN	1-RM	+16%
	College	6m	VOL	–	85	7.5	6	18	24–30			1-RM	+20%
		6m	NMES + VOL	2,500mo50	85	7.5	6	18	24–30			1-RM	+26%
													NMES + VOL > NMES = VOL
Willoughby & Simpson (1998)	Track and field	5f	NMES	2,500mo50	N/A	N/A	6	18	24–30	QF	DYN	1-RM & CMJ	+45% and +2%
		5f	VOL	–	85	7.5	6	18	24–30			1-RM & CMJ	+54% and +10%
	College	5f	NMES + VOL	2,500mo50	85	7.5	6	18	24–30			1-RM & CMJ	+80% and +25%
													NMES + VOL > VOL ≥ NMES
Maffiuletti et al. (2000)	Basketball	10m	NMES followed by 4 wk of standardized basketball training	100	80	16	4	12	48	QF	ISO	Isometric MVS	∼+45% // ∼+45%
	Nat											Eccentric MVS	+29–37% // +29–37%
												Concentric MVS	+30–43% // +30–43%
												CMJ	NS // +17%
												SJ	+14% // +18%

Table 2 continued

Authors	Sport and level	Sample size Sex	Design of training protocol									Athletic performance	
			Training modality	Frequency (Hz)	Training intensity (%MVC or RM)	Session duration (min)	Training (Weeks/sessions)		Nb of reps	Trained muscle	Mode	Recorded variables	Results
Maffiuletti et al. (2002a)	Volleyball Reg	10m	NMES & Plyo (i.e., 50 jumps per session) followed by 2 wk of standardized volleyball training	115–120	≥60	~16 & ~10	4	12	48 & 30	QF/TS	ISO	QF isometric MVS	+28% // +22%
												TS isometric MVS	+25% // +26%
												DJ	~+12% // ~+16%
												SJ	~+20% // ~+23%
												CMJ	~+10% // ~+14%
												Spike	~+8% // ~+12%
Malatesta et al. (2003)	Volleyball Reg	12m	NMES followed by 10 days of standardized volleyball training	105–120	N/A	~12	4	12	~20	QF/TS	ISO	SJ	NS // +6%
												CMJ	NS // +5%
												Repeated CMJ	+4% // +5%
Brocherie et al. (2005)	Ice Hockey Nat	9m	NMES	85	60	12	3	9	30	QF	ISO	Eccentric MVS	+24–37%
												Concentric MVS	+38–49%
												SJ	−8%
												CMJ	−6%
												DJ	−5%
												10-m skating time	−5%
												30-m skating time	NS
Babault et al. (2007)	Rugby Nat	15m	NMES	100	60	12 (for each muscle group)	6 + 6	18 then 6	36	QF/PF/ Gluteus	ISO	Eccentric MVS	+18%
												Concentric MVS	+10–19%
												Squat strength	+15%
												SJ	+10%
												CMJ	NS
												DJ	+7%
												20-m sprint time	NS
												50-m sprint time	NS
												Scrummaging strength	NS

Table 2 continued

Authors	Sport and level	Sample size Sex	Design of training protocol									Athletic performance	
			Training modality	Frequency (Hz)	Training intensity (%MVC or RM)	Session duration (min)	Training (Weeks/sessions)		Nb of reps	Trained muscle	Mode	Recorded variables	Results
Maffiuletti et al. (2009)	Tennis	5m/7f	NMES followed by 4 wk of standardized tennis training	85	~77	10	3	9	20	QF	ISO	Isometric MVS	~+50%
	Nat & reg											SJ	NS
												CMJ	+6%
												Repeated jump	NS
												2 × 5-m sprint time	NS
												2 × 10-m sprint time	−3%
Deley et al. (2011)	Gymnastic	8f	NMES	75	60	20	3 + 3	9 then 3	30	QF	ISO	Eccentric MVS	~+40%
	Nat & reg											Concentric MVS	~+25–40%
												SJ	~+21%
												CMJ	+10%
												Repeated jump	+20%
												Specific gymnastic jump	+15%
Billot et al. (2010)	Soccer	10m	NMES	100	60	12	5	15	36	QF	ISO	Isometric MVS	+27%
	Reg											Eccentric MVS	+22%
												Concentric MVS	+14−23%
												SJ	NS
												CMJ	NS
												10-m sprint time	NS
												Kicking performance	+7–10%

Data presented in this table were obtained from the trained limbs of young healthy athletes (~12–27 years)

// muscle performance was assessed after an additional specific training program, *1-RM* one-repetition maximal, *BB biceps brachii*, *CMJ* counter movement jump, *DJ* drop jump, *DYN* dynamic, *ISO* isometric, *LD latissimus dorsi*; *MVS* maximal voluntary strength, *Nat* national, *QF quadriceps femoris*, *Reg* regional, *Reps* repetitions (i.e., contractions), *SJ* squat jump, *TS triceps surae*. Others abbreviations have been already defined in Table 1 reported a 12.5% MVC increase with a training intensity amounting to 69% MVC. However, the lack of standardization for other stimulation parameters precluded comparative analyses between different NMES studies (Singer et al. 1987; and see below). Interestingly, it has been reported that the NMES-induced strength gains were positively correlated with the training intensity (Selkowitz 1985), thereby indicating that the higher the training intensity, the higher the efficiency of the NMES training (Fig. 1). To our knowledge, only one investigation has directly compared the effects of training intensity on muscle strength capacity (Lai et al. 1988) and consistently reported that the strength gains were higher when NMES exercises were performed at 50% MVC as compared to 25% MVC (Table 1). On that basis, we suggest that, under standardized stimulation conditions, training intensity is an important adjustable factor of NMES efficiency and should be carefully monitored and mentioned in all NMES studies.

Electrical current application through the skin results in activation of nociceptive receptors, thereby inevitably inducing discomfort, pain or burning sensations (Halback and Straus 1980). Given that the subjects' tolerance to electrical current strongly determines the training intensity, there is a considerable inter-individual variability in NMES response (Fig. 1) with some individual values exceeding the maximum voluntary force capacity. However, it is noteworthy that training intensity higher than MVC is scarce and has been mainly reported in subjects accustomed to discomfort associated to high training levels (Delitto et al. 1989). In previous studies related to NMES training, the training intensity ranged from 40 to 70% MVC (Gondin et al. 2005, 2006a; Maffiuletti et al. 2002b; Parker et al. 2003; Zory et al. 2010) (Fig. 2a). Consistently, Lieber and Kelly (1991) reported that electrically-evoked force reaching levels higher than 70% MVC are extremely rare. Even though the current intensity (or current amplitude) is usually increased up to the individual pain threshold in most of NMES studies, it would remain difficult to recruit all the motor units, especially those located far from the stimulating electrodes (i.e., in the deep muscular regions) (Maffiuletti 2010). The corresponding incomplete muscle activation could, therefore, explain the inability to produce electrically-evoked force equal to 100% MVC. This may explain why NMES is not more efficient than voluntary resistance training protocol for increasing muscle strength. As suggested by Vanderthommen and Duchateau (2007), the lesser force evoked with NMES could also be related to the recruitment of synergistic muscles during MVC performance which stabilize the posture, whereas such muscle activation is lacking during electrically-evoked contractions.

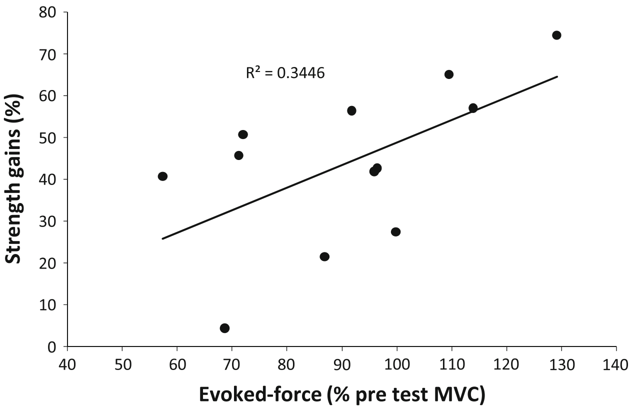

Fig. 1 NMES effectiveness (i.e., strength gains) is correlated with training intensity (i.e., electrically-evoked force). Of interest is the considerable inter-individual variability regarding NMES response (ranging from ~50 to ~130% MVC). It is noteworthy that the training intensity was expressed in percentage of pre-test MVC. Considering that voluntary strength increased throughout the training program, one could assume that the training intensity was likely overestimated in this study. Adapted from Selkowitz (1985)

Interestingly, several studies (Fahey et al. 1985; Selkowitz 1985) did not observe sex difference in NMES-induced strength gains although males were able to reach higher levels of current intensity than females (Alon and Smith 2005; Fahey et al. 1985). Considering that muscle cross-sectional area is usually larger in males than in females, one could suggest that, for a given stimulation electrode area, the amount of stimulated muscle was similar in men and women. Further studies would be warranted in order to carefully compare the activated muscle CSA between men and women, and magnetic resonance imaging based on T_2 measurements is a method of choice for such functional investigations (Adams et al. 1993; Gorgey et al. 2006).

We (Gondin, Brocca, D'Antona and Bottinelli, unpublished observations; Fig. 2) and others (Alon and Smith 2005; Balogun et al. 1993; Herrero et al. 2006; Laughman et al. 1983; Owens and Malone 1983; Parker et al. 2003; Selkowitz 1985) have previously observed that maximal tolerated current intensity increased during the first part of an NMES training program and then reached a steady state, thereby indicating that the sensation of discomfort could be decreased until a certain limit. On that basis, subjects could be asked to perform slight voluntary contractions when starting an NMES exercise so that pain or burning sensations could be reduced (Maffiuletti 2010). However, NMES should then be performed under resting conditions in order to avoid the confounding effects of voluntary contribution in monitoring the electrically-evoked force and the related training intensity. In addition, considering that both the electrically-evoked force and the current intensity plateaued during conventional NMES training program, NMES

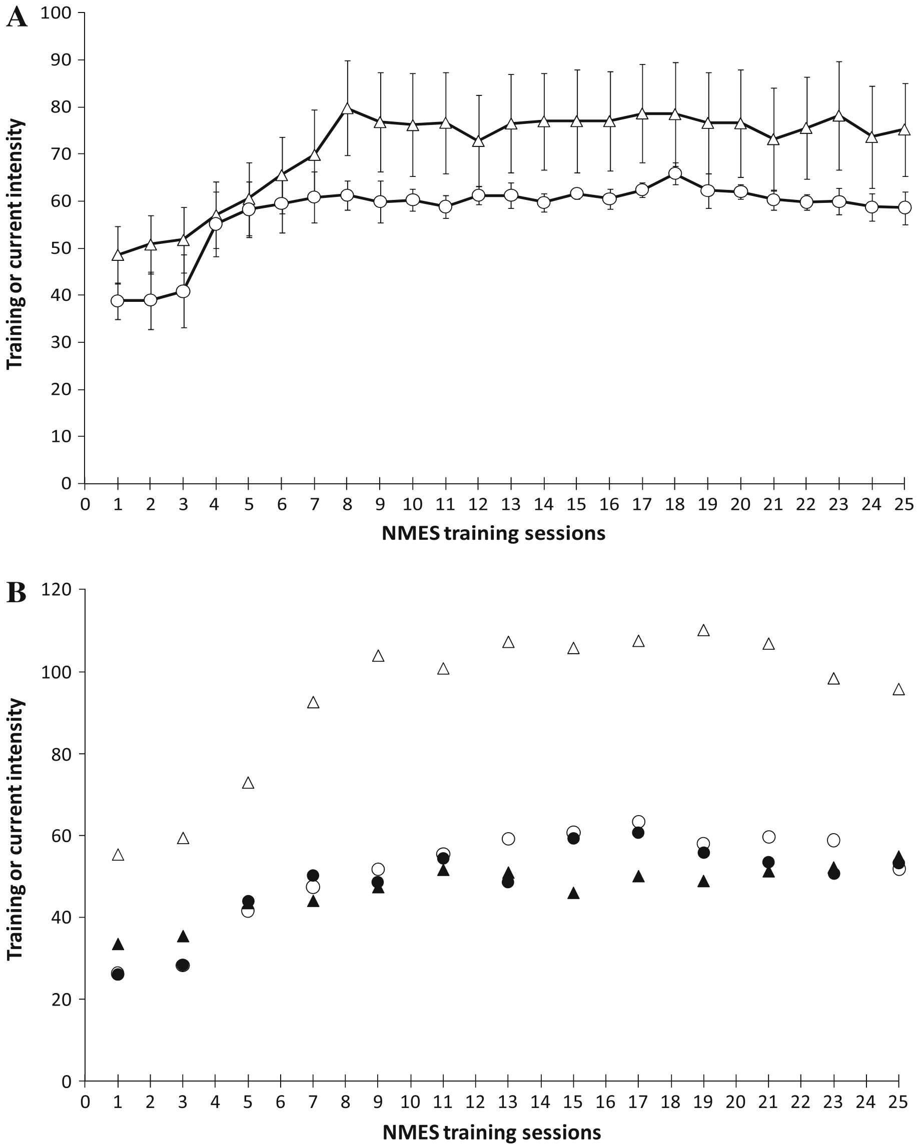

Fig. 2 **a** Maximal tolerated current intensity (*open triangle*, in mA) and training intensity (*open circle*; expressed in % of MVC recorded before each training session) throughout a training program consisting in 25 sessions (18 min) of isometric NMES over an 8-week period, with 3 sessions/week ($n = 8$ healthy subjects). Mean data ± standard error. **b** Individual values obtained in two representative subjects (*open* vs. *filled symbols*) during the corresponding NMES training program. *Triangles* and *circles* correspond to maximal tolerated current intensity (in mA) and training intensity (in % MVC), respectively. Note that despite a ~twofold difference in maximal tolerated current intensity, both subjects reached a similar evoked force, thereby illustrating the inter-individual differences in NMES response

should be combined with other training modalities if one aims at further improving muscle performance.

Other current characteristics (pulse duration, waveform…)

Although most researchers have used so far biphasic rectangular pulses, lasting between 100 and 500 µs and delivered at a frequency of ~50–100 Hz in order to reach high level of evoked force, no consensus has emerged regarding standardized optimal conditions of stimulation (Vanderthommen and Duchateau 2007). While alternating currents (also called "Russian current") have been initially used for NMES training (Ward and Shkuratova 2002), pulsed currents are now extensively used in healthy humans (Gondin et al. 2005; Herrero et al. 2006; Maffiuletti et al. 2002b). Interestingly, Aldayel et al. (2010a) recently reported that both alternating and pulsed currents led to similar force production during NMES, given that the remaining stimulation parameters were carefully standardized. On that basis, the waveform itself would not account for the variability of strength gains reported so far.

Design of training protocols

Although the "Russian" 10/50/10 sequence (i.e., 10 s of stimulation followed by 50 s repeated for 10 min) has been initially considered as the protocol leading to optimal improvement of muscle performance (Ward and Shkuratova 2002), significant strength gains have also been reported after the 6.25/20/17.5 stimulus regimen (Gondin et al. 2005, 2006a; Jubeau et al. 2006; Zory et al. 2010) so that further studies are required in order to better define the optimal stimulation protocol. From a practical point of view, it has been shown that NMES performed three times a week led to greater strength increases as compared to two sessions per week for the quadriceps muscle (Table 1) (Parker et al. 2003) and that 5-weekly NMES sessions increased abdominals MVC force more than 3-weekly sessions (Alon et al. 1992), thereby suggesting that the number of NMES training sessions also contribute to the magnitude of strength gains. It has to be underlined that growing evidence is emerging illustrating the potential damaging effects of a single bout of NMES (Jubeau et al. 2008; Mackey et al. 2008). However, changes in markers of muscle damage have been reported to be attenuated when the same NMES exercise was performed 2 weeks later (Aldayel et al. 2010b). On that basis, one could suggest that various strategies of muscle preconditioning such as increasing the training intensity, the number of contractions or muscle length gradually might be of interest for practitioners in order to minimize the magnitude of NMES-induced muscle damage.

Electrode configuration (size, type and positioning…)

Several authors (Ferguson et al. 1989; Lake 1992; Lloyd et al. 1986; Selkowitz 1989) have indicated that both the electrode size and positioning are critical for NMES effectiveness. In that respect, electrode size must be optimally matched to the stimulated muscle because too small electrodes would increase the current density and lead to more painful sensation (Alon 1985; Patterson and Lockwood 1993), whereas excessively large electrodes could stimulate undesired muscles (e.g., antagonists) and inevitably reduce the electrically-evoked force (Alon et al. 1994). Furthermore, higher evoked-force levels have been reached when the quadriceps muscle was stimulated with electrodes positioned longitudinally to the muscle fibers as compared to a transverse positioning (Brooks et al. 1990).

Nevertheless, one should keep in mind that NMES effectiveness is primarily determined by some intrinsic neuromuscular properties such as individual motor nerve branching (Lieber and Kelly 1991), which strongly determines response of the muscle to the application of electrical current over the skin (Fig. 2b), rather than to external adjustable factors. As a consequence, there would still be inter-individual differences in NMES response probably based on anatomical specificities (e.g., morphological organization of the axonal branches within the muscle) and so regardless of the selected stimulation parameters.

Conclusions and future directions

Short-term NMES training appears as an attractive tool for increasing muscle performance in both healthy humans and highly trained athletes although the effects of NMES on muscle fatigability required further investigations. Even though NMES is not more effective than voluntary exercise for improving muscle capacity, and pain or discomfort is the main limitation of this technique, this training modality imposes a specific muscle stress leading to the recruitment of motor units different from those activated throughout voluntary actions. As a consequence, NMES can be considered as an efficient and relevant complement to traditional voluntary strengthening programs. Given that NMES is mainly delivered under non-specific (i.e., isometric) conditions, coaches and/or practitioners should use different dynamic exercises (e.g., plyometrics, sprint, vertical jump) for an optimal improvement of muscle performance. On that basis, future studies should focus on the chronic effects of NMES-induced dynamic contractions and on the optimal combination of NMES with various dynamic training modalities for increasing both voluntary strength and anaerobic power production. Additionally, further studies are needed in order to better understand the influence of reduced NMES training volume (i.e., tapering) on muscle function and to design the optimal training protocol and periodicity. Considering that NMES effectiveness is, at least partially, related to stimulation parameters, the corresponding training modalities should be carefully mentioned in future investigations.

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