PERCUTANEOUS ELECTRICAL STIMULATION IN STRENGTH TRAINING: AN UPDATE

BERNARDO REQUENA SÁNCHEZ,[1] PAULINO PADIAL PUCHE,[1] AND JUAN JOSÉ GONZÁLEZ-BADILLO[2]

[1]Department of Physical Education and Sport, University of Granada, Granada, Spain; [2]Spanish Olympic Committee, Madrid, Spain.

ABSTRACT. Requena Sánchez, B., P. Padial Puche, and J.J. González-Badillo. Percutaneous electrical stimulation in strength training: an update. *J. Strength Cond. Res.* 19(2):438–448. 2005.—Numerous studies have used percutaneous electrical stimulation (PES) in the context of training programs to develop strength and physical performance in healthy populations (sedentary or trained). Significant increases in muscle and fiber cross-sectional area, isokinetic peak torque, maximal isometric and dynamic strength, and motor performance skills have been found after PES training. These strength gains are explained on the basis of the characteristics of PES motor units (MUs) recruitment: (a) a continuous and exhausting contractile activity in the same pool of MUs during the entire exercise period, (b) a supramaximal temporal recruitment imposed by the high frequency chosen (up to 40 Hz), and (c) a synchronous recruitment of neighboring fibers. The PES training method is complementary to voluntary training, mainly because the application of PES causes an unconventional spatial recruitment of MUs that, depending on the muscular topography, may entail the preferential recruitment of the fast-twitch MUs. In addition, the method does not specifically develop elasticity in skeletal muscle, and it must be accompanied by a technical workout.

KEY WORDS. electrical stimulation, skeletal muscle, weight training, performance

INTRODUCTION

Percutaneous electrical stimulation (PES) is the application of electrical stimulation to produce skeletal muscular contractions as a result of the stimulation of peripheral nerves (41). A great number of studies have confirmed the efficacy of this method in orthopedic rehabilitation and physical therapy; in the treatment of peripheral nervous system lesions, PES has been found to decrease muscle atrophy, weakness, and wasting (for review, see 29). However, a great variation has been reported concerning the ability of PES to increase muscular strength and sport performance, as compared with traditional training in healthy populations (sedentary individuals or athletes; Table 2).

The present review reports data exclusively in relation to the use of PES training in healthy, noninjured subjects to generate muscular strength, using moderate and high stimulation frequencies (higher than 40Hz) and aiming to improve performance. Therefore, the objectives of this article are to examine the conclusions given by the researchers who have studied the metabolism and the contractile activity in the human muscle during the application of PES; to identify the mechanisms of strength gain with PES; and to show the most representative results published on muscular strength after PES training.

MOTOR UNIT RECRUITMENT DURING ELECTRICALLY INDUCED CONTRACTIONS

Motor Units Recruitment Order

Generally, it is accepted that recruitment and derecruitment of motor units (MUs) during voluntary muscular contractions (VCs) follow the Hennemann "size principle" (24), although there are a few noted exceptions (55). However, several studies involving electrical stimulation have suggested selective and preferential recruitment of fast-twitch MUs (11, 15, 33, 70), which is to say, a reverse order of recruitment of MUs (16).

In animal studies, it has been shown that with direct nerve stimulation by means of implanted electrodes, the recruitment order of MUs during increasing stimulation is the opposite of the order during voluntary recruitment (22, 28). This reverse order of activation can be explained on the basis of biophysical principles largely related to axon diameter (19, 37). Thus, the efferent axons of larger diameter (which are part of fast-twitch MUs) with low axonal input impedance are more excitable to electrical stimulation (22, 37).

Nevertheless, a significant controversy exists regarding the recruitment order of MUs during PES of a motor nerve or of a muscle motor point in humans (24, 40). Studies both support (11, 33, 47, 64, 70) and refute (1, 6, 24, 40, 62) the reversal of MU recruitment during PES. These controversial observations could be related to differences in experimental approaches and muscles that were studied (Table 1).

Two factors have been suggested as the main causes of the possible reverse order of recruitment of MUs during PES: the diameter of the parent motoneuron axon, as well as axonal branches within the muscle (40), and the feedback effects of cutaneous afferents (27, 70). The stimulation of cutaneous receptors that occurs with PES can alter the population of MUs that is activated by voluntary and H-reflex means (70). It has been confirmed that the stimulation of cutaneous receptors induces excitatory afferents in fast-twitch MUs and inhibitory afferents in those of slow-twitch MUs (27, 70).

However, apart from direct nerve stimulation, other factors that argue in favor of a much less reverse orderly recruitment of MUs during the application of PES have been suggested. One factor is the size of the motoneuron branches within the muscle (6, 24, 40). Some terminal branches of fast-twitch and large MUs could be smaller than those of slow-twitch and small MUs and, therefore, would be activated only by higher current levels than slower MUs (40). A second factor is the location and the orientation of the parent axon, as well as axonal branches in the current field (6, 24, 40). Those that are closer to

TABLE 1. Summary of the main studies surveyed on neuromuscular recruitment during the application of PES.*

Reference	Experimental approaches	M	Main Result	MU recruitment order
Cabric et al. (11)	Muscle biopsies before and after PES training program	QF	Type II fibers exhibit more adaptation—nuclear volume, mitochondrial fraction, and heterochromatin fraction of myonuclei—than type I fibers.	PES preferentially activates the largest MUs
Sinacore et al. (64)	Muscle biopsies before and after PES training session	QF	Glycogen depletion of type II muscle fibers. The type I fibers did not demonstrate glycogen depletion.	PES preferetially activates the largest MUs
Saltin et al. (62)			Glycogen depletion of both slow and fast fibers.	Larger and smaller MU's are recruited at low contraction intensies.
Trimble and Enoka (70)	Muscle twitch time-to-peak	QF TS	Twitch time-to-peak increases curvilinearly with increasing PES, whereas it decreases with increasing H-reflex responses. Whereas faster MUs are recruited as low intensity during PES, slower MUs are activated with increasing PES intensity, thereby lengthening the twitch time-to-peak of the compound response.	PES preferentially activates the largest MUs
Heyters et al. (33)		FDI AP TS	Increased twitch time-to-peak with increased PES intensity in muscles with different functions and fiber compositions.	PES preferentially activates the largest MUs
Knaflitz et al. (40)	Muscle fiber conduction velocity and the frequency of the power spectrum of the EMG	TB	Reverse sequence of MU activation during PES in only 28% of their experiments. In the rest of the experiments (72%), conduction velocity increased with increasing stimulation current, indicating a recruitment order similar to that of VC.	PES does not reverse the normal order of MU activation.
Binder-Macleod et al. (6)	Force-frequency relationship and fatigability of MUs with progressively higher intensities of stimulation	QF	For force levels between 20 and 50% of MVIC, there were few changes in the force-frequency relationship and the fatigability of the recruited MUs. Increasing the intensity to produce tetanic contractions equal to 80% of MVIC produced a shift in the normalized force-frequency relationship.	Larger and smaller MUs are recruited at low contraction intensities.
Feiereisen et al. (24)	Spike-triggered averaging technique	TB	During PES at the muscle motor point, MU pairs showed a reversal of recruitment order in 28% and 35% of the observations, respectively, when the pulse durations were 1.0 or 0.1 ms.	Larger and smaller MUs are recruited at low contraction intensities.
Maffiuletti et al. (47)	Post-activation twitch potentiation before and after PES training program	TS	Postactivation twitch potentiation significantly increased by 11.9% after PES training, whereas no changes were observed in the control group.	PES preferentially activates the largest MUs.

* AP = adductor pollicis m.; FDI = first dorsal interosseous m.; M = muscular group; MUs = motor units; MVIC = maximal voluntry isometric contraction; PES = percutaneous electrical stimulation; QF = quadriceps femoris m; TB = tibialis anterior m.; TS = triceps surae m.

the electric field should be recruited more easily than those deeper in the muscle mass (24, 42). PES creates an electrical field that is superficial at low intensities and deepens with higher intensities (1, 42, 72, 73). In addition, the morphological organization of the different types of MUs varies depending on each muscular group (i.e., in quadriceps femoris (QF) MUs with large diameter axons are often located on the (MUs) muscle surfaces (44), whereas in tibialis anterior, the larger diameter axons appear to be located deep within the muscle mass (31). Along that line, Heiters et al. (33) found that subsequent to PES training, the range of twitch time-to-peak was greater in muscles with a larger proportion of fast MUs on their surfaces.

There are two inferences to be made on the basis of the studies surveyed. First, the recruitment pattern during PES is different from that reported during VC (72). Thus, with PES, both the larger, faster contracting, more fatigable MUs and the smaller, slower contracting, fatigue-resistant MUs appear to be recruited at relatively low contraction intensities (6, 16). In contrast, during VCs, the slower contracting and more fatigue-resistant MUs are recruited first (55). Therefore, in percutaneous, electrically evoked contractions, there is at least a partial reversal in the order in which MUs are recruited (6, 24). Second, the existence of higher or lower preferential recruitment of fast-twitch MUs during PES depends on several factors, including the muscular group selected (i.e., QF vs. tibialis anterior), the morphological organization of the axonal branches of each subject, and the location of the electrodes (1).

Synchronous Depolarization

With PES, the normal voluntary physiologic recruitment strategy (i.e., MUs fire asynchronously) is disrupted, and instead, all motoneurons in the area of current flow are depolarized (1, 50), entailing an artificially synchronous MU firing (16).

Constant, Higher Firing Rates

Unlike VCs, during electrically induced contractions, a constant discharge frequency in the same pool of MUs is produced during the entire exercise period (24, 73) and higher frequencies designed to ensure tetanic contractions are used; thereby, there is an optimal force development of fast MUs (higher to 40 Hz; 75). Thus, it has been suggested that the high frequency of activation with PES may result in fusion for even the fastest MUs (16).

MAIN CHARACTERISTIC PHYSIOLOGICAL EFFECTS IN THE APPLICATION OF PES

Human Muscle Energetics During PES

Little is known about muscle metabolism during PES at moderate and high frequencies greater than 40 Hz. The adenosine triphosphate (ATP) requirements during high intensity-short duration contractions, such as the tetanic contractions that occur during PES, are supplied primarily by phosphocreatine (PCr) and glycogen degradation with lactate production (anaerobic glycolysis; 35, 38, 49, 59, 66). Oxidative phosphorylation in the mitochondria is the main mechanism for ATP resynthesis during recovery (35). Kim et al. (38) showed that during an incremental 1-legged dynamic knee extension exercise test, the lactate and ammonia efflux from the leg were higher with PES

than during VCs, and the difference became larger with increasing exercise intensity ($p < 0.05$). Hultman et al. (35) showed that a PCr hydrolysis rate of 5.3 mmol·kg^{-1}·s^{-1} measured during the initial 5 seconds of PES of the QF at a stimulation frequency of 50 Hz declined progressively as stimulation continued, to 2.2 mmol·kg^{-1}·s^{-1} between the 10th and 20th second of stimulation and 0.2 mmol·kg^{-1}·s^{-1} between the 20th and 30th second of stimulation. Furthermore, the rate of ATP production from anaerobic glycolysis declined from 4.5 mmol·kg^{-1}·s^{-1} during the first 20 seconds of contraction, to 2.1 mmol·kg^{-1}·s^{-1} during the final 10 seconds of contraction. Similar findings have been reported in other studies (9, 36).

Those studies which have assessed human muscle energetics during PES by means of nuclear magnetic resonance spectroscopy (NMRS) are representative also (49, 50, 59, 73, 74). This noninvasive technique has the further advantage of examining the same representative mass of tissue before, during, and after the exercise (50). In spite of the heterogeneity of protocols used, in all of the studies surveyed, the spectral modifications reflect that tetanic electrical stimulations are responsible for an overrated metabolic demand for the required force development (49, 59, 73, 74). Vanderthommen et al. (74) monitored the inorganic phosphate/creatine phosphate (Pi/PCr) ratio and pHi in a superficial region of the vastus medialis during PES and during VC. In both modes, a workload corresponding to 20% of MVC was applied during 64 isometric contraction (5.5 seconds) and relaxation (5.5 seconds) cycles. With PES, the QF was stimulated with a 50-Hz frequency using a 7-seconds-on (1 second rise time, 5.5 seconds plateau and 0.5 second fall time) and 5.5-seconds-off program for 13 minutes, 20 seconds. They confirmed that during exercise, the Pi/PCr ratio was higher (0.36 vs. 0.14) and the pHi was lower (6.85 vs. 7.07) during PES than during VC. Therefore, it has been shown that for the same external work production, there is a different metabolic solicitation in the PES of the QF than in the VC of the QF.

The important metabolic demand during PES contraction (Figure 1) with more pronounced activation of the anaerobic metabolism of the muscle is explained by several authors (4, 5, 49, 64, 66, 73, 74) mainly on the basis of the characteristics of the PES MU recruitment: (a) a continuous and exhausting contractile activity in the same pool of MUs during the entire exercise period (73); (b) a supramaximal temporal recruitment imposed by the high frequency chosen (up to 40 Hz); (c) a synchronous recruitment of neighboring fibers (1, 72); and (d) a higher or lower preferential recruitment of fast-twitch MUs (Table 1).

Hemodynamic Responses to Voluntary vs. Electrically Evoked Contractions

Little is known about circulatory responses and local aerobic metabolism in the electrostimulated human muscle (72, 73) at moderate or high frequencies. In several studies (38, 52, 73, 78), the circulatory responses to electrically evoked and voluntary muscle contractions in healthy subjects were compared, with contradictory results. In this regard, it is representative of the work carried out by Vanderthommen et al. (73). In that work, the blood flow was measured by means of a magnetic resonance spectroscopy (P NMR) streptoscopy, showing that during a bilateral simultaneous isometric exercise using
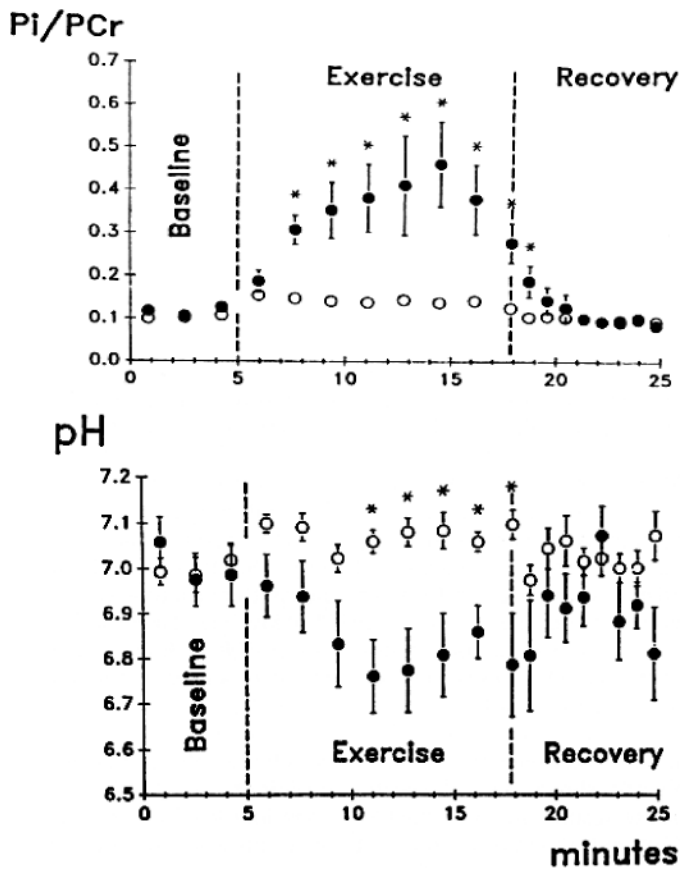
Pi/PCr

FIGURE 1.   Changes in Pi/PCr ratio and intramuscular pH during baseline, exercise, and recovery for voluntary muscular contractions (open symbols) and percutaneous electrical stimulation (closed symbols) (mean ± *SEM, n* = 10). * = statistical difference (*p* < 0.05) between the two contraction modes. Reprinted with permission from *Int. J. Sports Med.*(40). Pi/PCr = inorganic phosphate/creatine phosphate.

PES on one QF and VC for the other (with a workload corresponding to 20% of MVIC), higher blood flow is induced by tetanic electrical stimulation than by VC (24.4 ± 14.6 vs. 8.6 ± 3.6 mL·min^{-1}·100g^{-1}, *p* < 0.001).

It has been suggested that the use of PES at moderate and high frequencies greater than 40Hz leads to maximal tetanic contractile activity in neighboring fibers (42) that induces local capillary collapse, which reduces oxygen supply during the contraction phases (51). Thus, metabolites liberated during contraction (i.e., hydrogen ions, adenosine or phosphate; 43) progressively involve a local vasodilatation (72) and an increase in local blood flow and in oxygen supply during the periods between contractions. Therefore, the hemodynamic responses to electrically evoked contractions are caused mainly by local mechanisms (52).

MAIN RESULTS OBTAINED AFTER PES TRAINING

Muscle Cross-Sectional Area

The results in the literature surveyed are very diverse. Recently, it has been shown that the concurrent application of PES during coupled concentric-eccentric isokinetic actions increases the cross-sectional area (CSA) of the QF (measured through NMRS) at a rapid rate (~10%

in 8 weeks) in healthy sedentary (61) and recreationally resistance-trained individuals (3+ years of training; 67). Turostowski et al. (71) used an x-ray computerized tomography technique and found a significant increase of the CSA of the right QF: 8% using PES vs. 2% using voluntary training. However, using similar diagnostic imaging machines, other studies did not show increases of the CSA subsequent to PES training. Martín et al. (48) did not observe any variation in the CSA of the triceps surae on trained subjects after 12 training sessions. These results coincide with those obtained by Singer (65) and Erikson et al. (20) after applying 20 sessions of PES on injured QFs. These authors (20, 48, 65) have suggested that PES training improves motor control and muscular contractility without modifying hypertrophy. On the contrary, the studies where muscle growth was found after PES training (61, 67, 71) differ methodologically in two important ways: PES was applied on the QF of healthy subjects, and, in two of these studies (61, 67), a concurrent PES application mode was used. In both studies, it was suggested that the main reason for such impressive growth (1.25% per week) was the PES supplementation during the eccentric component of the exercise. Westing et al. (80) found that the concurrent application of PES during eccentric contractions generates a muscle-specific tension greater than that of concurrent application during maximal voluntary isometric or eccentric muscle actions. Furthermore, Dudley et al. (17) showed that with PES, force of the QF is about 40% greater during eccentric than during isometric muscle actions. Therefore, it has been suggested that the large increase in muscle size shown in those studies (61, 67) is an adaptive response to extra eccentric loading imposed by the concurrent application of PES with the chosen training protocol.

Fiber-Type Composition

Most of the studies on the effects of PES on skeletal muscle fiber types of healthy individuals have been based upon the use of very traditional histochemical schemes to characterize skeletal muscle fiber types (3, 11, 14). For instance, Delitto et al. (14) carried out three percutaneous needle biopsies on the vastus lateralis of the left QF. By means of the myofibrillar ATP-based histochemical technique, they found that the distribution of fiber types after a period of PES training was significantly different (*p* < 0.05); there were fewer type I and more type II fibers. These authors suggested the possibility of a conversion from type I to type II fibers. On the contrary, Bigard et al. (3) used the same technique on the triceps brachialis m. on a sample of 8 male primates (rhesus monkeys) which were strictly untrained prior to the PES training program; the researchers found that the distribution of the fibers was not altered.

There is sufficient evidence that many fibers identified histochemically as pure fibers (e.g., expressing a single myosin heavy chain [MHC] isoform) are actually hybrid fibers (e.g., coexpressing 2 isoforms; 2). Consequently, these fibers have been misclassified in the above-mentioned studies, and this has important functional implications when trying to correctly evaluate fiber-type plasticity after PES training. It is reasonable, therefore, to assume that the magnitude of muscle-fiber–type transitions has been underestimated in previous human PES studies also (11, 14). Thus, the work carried out by Perez et al. (56) is representative. In this study, the effect of a

6-week PES protocol—30 minutes per session per day, 3 days per week, 45–60 Hz, 12 seconds on, 8 seconds off—was assessed on MHC composition, based on electrophoresis, and MHC-based fiber type distribution, based on immunohistochemistry techniques. These authors showed that PES training produced a significant decline in the proportion of both MHC-IIX (44%, $p < 0.01$) and MHC-I (17%, $p < 0.05$) isoforms, and the proportion of MHC-IIA increased very significantly (39% vs. week 0, $p < 0.01$). Furthermore, the percentage of pure IIA fibers increased (63%, $p < 0.001$), whereas percentages of types IIX, I, and I + IIA fibers decreased after PES training. Similar findings have been reported in 2 human studies associated with short-term sprint training (2, 21). The authors of the 3 latter studies interpreted these observations as a bidirectional transformation of MHC isoforms from both MHC-IIX and MHC-I toward an increased expression of MHC-IIA during the early phase of sprint or PES training.

Fiber Cross-Sectional Area

Delitto et al. (14) achieved a decrease in type IIa and IIb fiber cross-sectional area (FCSA; average of 25% and 33% respectively, $p < 0.05$) and an increase in type I FCSA (13%, $p < 0.05$). It is difficult to explain the reason for these results, more so because strength performances were enhanced. The authors suggested that the fast-twitch fibers of the subject had increased working capacity to the maximum, and that the strength gains responded to an adaptation of a neural nature. St. Pierre et al. (68) confirmed a decrease in the fast-twitch fiber areas poststimulation ($\sim 20\%$, $10,790 \pm 2,310$–$8,670 \pm 2,030$ μm^2) on 10 healthy subjects, after training with PES during 7 consecutive sessions (with only one day of rest) and using the protocol proposed by Kots (79). These results with healthy subjects contrast with those published showing cellular hypertrophy in patients following anterior cruciate ligament repair (81). This is why Delitto et al. (14) suggest that entirely different mechanisms are involved in strength training with healthy subjects vs. strength training with subjects with muscle atrophy. Nevertheless, other studies show different results. Cabric et al. (11) found an increase of the FSCA (3,317.4 vs. 3,840.4 μm^2; $p < 0.05$) in the triceps surae of the group, from a sample of 22 male physical education students, that trained with a 50-Hz frequency. Bigard et al. (3) obtained similar results, though not on humans. They found that the effect of PES on the FSCA was not selective and both the slow-twitch (type I) and the fast-twitch fibers (type II) were hypertrophied. It has been suggested that protocols involving high-frequency stimulation (50–100 Hz) are more strength-oriented and thus more likely than medium-to-lower frequency protocols to induce a higher degree of hypertrophy and less remodeling of the contractile and metabolic properties of muscle fibers (56).

Isokinetic Peak Torque

The majority of the studies surveyed show significant increases in the isokinetic peak torque (IPT) after PES training. The improvements have been found when applying PES to the QF (7, 23, 45, 58, 61, 71, 76), elbow flexors (12), triceps surae (48), plantar flexors (47), and dorsal muscles (57).

Significant improvements have been found on the QF at concentric angular velocities ranging from 15–360° × seg^{-1} (58). The largest improvements occur as the magnitude of the concentric angular velocity increases (7, 45, 58). Maffiuletti et al. (45) found an increase of 43% at 360°·s^{-1} ($p < 0.01$) vs. 15% at 60 and 120°·s^{-1} ($p > 0.05$) in basketball players from national divisions. This tendency—larger gains in IPT at higher angular velocities—is found also in other muscular groups such as the latissimus dorsi muscle (57) and the elbow flexors (12).

On the one hand, all the studies surveyed that assess the effects of PES training by means of torque gains under eccentric conditions show significant improvements of the IPT (12, 45, 47, 57, 76). Pichon et al. (57) applied PES on the latissimus dorsi muscle of 14 swimmers at the national level during their competition period. They confirmed that the largest improvements of IPT occurred in eccentric actions (24.1% at 60°·s^{-1}). Thus, only under eccentric conditions ($-60°·s^{-1}$), the peak torque measurement and the sprint swimming performances before or after training were related together ($r = -0.77$). In a recent study (47), it has been shown that after 16 PES sessions on the plantar flexor muscles, improvements in IPT were registered only under isokinetic eccentric actions ($p < 0.001$ for 120°·s^{-1} and $p < 0.05$ for 60°·s^{-1}), whereas the concentric torque values were not significantly different after training.

On the other hand, it has been shown that with PES training, the time to peak torque under concentric conditions fell only for the 3 faster velocities (12% at 180°·s^{-1}, 18.2% at 300°·s^{-1}, and 24.6% at 360°·s^{-1}, $p < 0.001$; 71).

Therefore, in isokinetic actions, the largest improvements found in ITP have occurred in concentric actions performed at high velocities up to 180°·s^{-1} and in eccentric actions. These results have been explained on the basis of a preferential adaptation of the fast-twitch fibers. Bear in mind that fast-twitch fibers are preferentially recruited during eccentric contractions (25, 55) and are recruited increasingly at high concentric velocities (13, 26). A preferential recruitment of large MUs during PES has been suggested as the main mechanism responsible for these strength gains (12, 45, 47, 57).

Maximal Isometric Strength

Just about all of the studies surveyed—save for some exceptions (60)—show significant improvements of maximal isometric strength (MIS) by using PES training (29). The enhancements achieved in the QF range from 7% (23) to 62.4% (77). Numerous investigations have compared submaximal PES with VCs of similar duration in healthy muscles (for review see 29, 63). In these studies, it was shown that the figures obtained for strength induced by isometric PES training could be as large as, but no greater, than those induced by voluntary isometric exercise (63).

There is a close connection between the training position and the gain in strength. It has been suggested that the increase in strength after voluntary isometric training (39) and PES training (12, 48) is angle specific. The angle-specificity of isometric training has been attributed to some form of neural adaptation, with a greater increase in MU activation at the trained joint angles (39). Colson et al. (12) show that subsequent to applying PES isometrically in a 90° flexion on the right elbow flexor muscles, the torque gains observed during isometric flexions were associated with a significant increase in the EMG-RMS activity at 90° and 120° of elbow flexions. It

has been recently confirmed that, after 4 weeks of PES training on the plantar flexor muscles, the isometric voluntary torque increased only at the training angle ($+8.1\%$, $p < 0.05$). This increase in strength was accompanied by a significant increase of the EMG activity of the agonist muscles, no changes in antagonist coactivation, and enhanced maximal voluntary activation (11.9% after training; 47). In the literature surveyed, it has been suggested that the increases in MIS are largely due to an increase in activation of the stimulated (agonist) muscles (possibly due to an increase in the quantity of the neural drive to muscle from the supraspinal centers; 12, 54) and to changes at a peripheral level, through preferential adaptation of the type II MUs (47).

Maximal Dynamic Strength

Few studies have assessed the effect of PES training on maximal dynamic strength (MDS). They all show significant improvements in comparison with the control or reference group (14, 77, 82, 83). Willoughby et al. (82, 83) applied PES statically and with identical stimulation protocols and found increases of 45% (70.07 ± 18.87–92.22 ± 16.74 kg for absolute strength, $p < 0.05$) in the bilateral knee extension exercise and 16% (0.456 ± 0.054–0.528 ± 0.058 for relative strength [strength per kg of body weight], $p < 0.05$) in the barbell-preacher curl exercise. Said authors obtained improvements for the same gestures of 79.5% (71.94 ± 11.28–120.67 ± 13.58 for absolute strength, $p < 0.05$) and 26% (0.489 ± 0.020–0.618 ± 0.033 for relative strength, $p < 0.05$), respectively, after concurrent application with weight training.

Delitto et al. (14) applied PES training parallel to the usual strength training of the athlete and obtained an improvement of 18.8% (20 kg) in squat. This increase is especially relevant because (a) it was obtained in a 27-year-old elite athlete with 11 years of competitive experience; it has been observed that elite lifters generally do not show such increases over 2 years of regular training (30); and (b) the improvement was obtained in a technical gesture frequently practiced by the subject. However, in this study it must be remembered that the chosen subject was able to support 200-mA–intensity currents, which made it possible for the average electrically evoked isometric torque throughout the entire experiment to be 112% of the MVIC. In addition, the limitations of a single-subject design experiment must be taken into account when generalizing these results.

Therefore, PES constitutes an efficient training method to increase MDS applied in regularly practiced gestures. Furthermore, it has been confirmed that larger increases were found by means of the concurrent application against strength training with PES or by means of voluntary training. One of the main reasons for such improvements would be the PES supplementation during the eccentric component of the exercises (34, 82). The large fast-twitch MUs appear to be preferentially recruited during voluntary eccentric actions (25, 55), as well as during the application of PES (Table 1).

Motor Performance Skills

Whereas isometric and isokinetic strength gains from PES regimens are clear from the literature, few studies actually show carry-over in motor performance skills gains.

PES Training and Vertical Jump. To begin with, in order to analyze the results offered, the type of vertical jump selected must be taken into account, for each technique implies a different muscular activation (10). During the countermovement jump (CMJ; starting from a standing position, then squatting down to a knee angle of 90 $\pm$ 5° and then extending the knee in one continuous movement), more power is used during the concentric phase. The stretch-shortening cycle (SSC) allows elastic energy to be stored and then reused, something that cannot happen during squat jump (10; SJ; starting from a static semisquatting position, knee angle 90°, and without any preliminary movement). Most of the studies surveyed have used SJ (32, 45, 46, 69), CMJ (45, 46, 69, 82), and drop jump (46, 69) (DJ; jump from a fixed height). Some studies (20, 77, 84) do not specify the execution technique of the vertical jump used for the test, and therefore, their results cannot be compared with the others.

Regarding SJ, the observed improvements are similar after applying static PES on the QF. Maffiuletti et al. (45), after 4 weeks of PES training in addition to standardized basketball training, obtained an improvement of 14% in the SJ (44.8 ± 1.0 vs. 51.0 ± 1.3 cm, $p < 0.01$). A similar enhancement (34 vs. 39 cm, $p < 0.05$) was found by Taillefer (69), although in his study, the training lasted for 10 weeks, and the group that trained with PES on the gastrocnemius muscles (as well as on the QF) increased the SJ by 24% (29 vs. 36 cm, $p < 0.05$).

Only 1 study has been surveyed in which the effect of concurrent application of PES (PES + weight training) on the QF has been assessed by means of SJ (69). It was found that the group that trained concurrently with eccentric actions improved by 18% (28 vs. 33 cm, $p < 0.05$), against the 7% improvement obtained by the group that trained concurrently with concentric actions. Static PES was also applied to the gastrocnemius muscles of both groups.

Regarding CMJ, the application of PES training for 4 weeks through a static method on the QF did not entail significant enhancements in the CMJ height (45, 82). It has been suggested that improvements in the strength of muscles involved in performing complex movements using elastic energy (such as CMJ) require a longer period of specific training before beneficial effects are observed in jumping performance (8, 46). Thus, Maffiuletti et al. (45) observed that CMJ height increased significantly (17%) after an additional 4-week standardized basketball training.

However, several authors (69, 82) have come up with the possibility that supplementary dynamic contractions with PES produce strength increases that may directly relate to improved functional performance. Thus, Willoughby et al. (82) showed improvements of 25% after applying PES continuously during the concentric and eccentric phases of the dynamic contraction. These authors explain their enhancements on the basis of the PES supplementation during the eccentric component of the exercises.

Finally, in a recent study (46), the effects of a 4-week training program combining (in the same session) PES of QF and plantar flexors muscles with plyometric exercises on different vertical jumps on subelite volleyball players were investigated. The findings of this study confirmed the primary results of several others (8, 45, 69), showing that (a) initial adaptations in vertical jump performance after PES training are more rapid for SJ than for CMJ; (b) spike height—the most specific volleyball jump—significantly increased by 8% at the end of the PES training program and by 12% after an additional 2-week specific training; (c) in a training program aimed at improving

TABLE 2. The significative strength gains obtained after applying PES training in healthy subjects (summary of 18 studies).

Reference	Subjects	M	MIS (torque-angle/%)	−120°·s⁻¹	IPT (torque angular velocity/%)							MDS (gesture/%)	Vertical jump (type/%)	MCSA (%)
					−60°·s⁻¹	60°·s⁻¹	120°·s⁻¹	180°·s⁻¹	240°·s⁻¹	300°·s⁻¹	360°·s⁻¹			
Maffuletti et al. (47)	14, healthy men	TS	0°/8.1 (0° foot flexion of 90° relative to the leg axis)	13.1	10.8	—	—	—	—	—	—	—	—	—
Bircan et al. (7)	30, medical faculty students	QF	—	—	—	14.4 20.7	18.5 22.7	—	—	—	—	—	—	—
Stevenson and Dudley (67)	18, resistance-trained subjects	QF	—	—	−70°·s⁻¹ 24/28**	70°·s⁻¹ 50/54**	—	—	—	—	—	—	—	11
Maffuletti et al. (45)	20, basketball players	QF	55°/* 65°/* (0° full extension)	29	37	—	—	30	32	36	43	—	SJ/14 CMJ/17	—
Colson et al. (12)	17, physical education students	EF	60°/47.5 ± 7.2 120°/33 ± 13.5 (0° full extension)	10	*	—	11.4	*	18.4	—	—	—	—	—
Willoughby and Simpson (83)	29, track & field athletes	QF	—	—	—	—	—	—	—	—	—	Bilateral knee extension exercise/S: 45.61 ± 4.12 D: 79.54 ± 4.98	CMJ/D iso+conc: 25.18	—
Van Gheluwe and Duchateau (76)	10, physical education students	QF	100%/20% (0° full extension)	—	19.3	23.8	—	—	—	—	—	—	—	—
Taillefer (69)	35, physical education students	QF TS	—	—	—	—	—	—	—	—	—	—	SJ/ S: 14 D+isom: 24 D+conc: 7 D+exc: 18 DJ20-DJ40-DJ60/ D+exc: 11-6-15 CMJ/ S: 18 D+isom: 11 D+conc: 3 D+exc: 9	—
Willoughby and Simpson (82)	23, basketball players	EF	—	—	—	—	—	—	—	—	—	Seated barbell preacher curl/ S: 13.6, D: 20.8	—	—

TABLE 2. Continued.

Reference	Subjects	M	MIS (torque-/angle/%)	IPT (torque angular velocity/%)									MDS (gesture/%)	Vertical jump (type/%)	MCSA (%)
				$-120°$ $s^{←}$	$-60°·s^{-1}$	$60°·s^{-1}$	$120°$ s^{-1}	$180°$ s^{-1}	$240°$ s^{-1}	$300°$ s^{-1}	$360°$ s^{-1}			
Ruther et al. (61)	16, healthy sedentary adults	QF	—	$±1.31$ rad·s^{-1}/56(†**)								—	—	10
Pichon et al. (57)	14, sprint swimmers	D²	140°/21 (0° complete arm flexion)		24.1	*	*	10.3	14.4	14.7	*	—	—	—
Martin et al. (48)	12, physical education students	TS	15°/33.8 ± 10.2 −15°/10.3 ± 4.2 (0° foot flexion of 90° relative to the leg axis)		1.05 rad·s^{-1}/26.5 ± 9.6 6.28 rad·s^{-1}/8.1 ± 2.1							—	—	—
Miller and Thépaut-Mathieu (53)	32, physical education students	EF	25°/15.6		—	—	—	—	—	—	—	—	—	—
Turostowski et al. (71)	20, physical education students	QF	—		30°·s^{-1} 9.4	5.6	—	—	—	—	—	—	—	8
Venable et al. (77)	33, college students	QF	35°/62.4 50°/47.6 60°/22.2		—	—	—	—	—	—	—	Squat/20.6	Not specific/3	—
Portmann and Montpetit (58)	33, track and field athletes	QF	S: 90°/21.4 D: 90°/17.8		3.14 rad·s^{-1}/S and D: 27.2 and 0.26 rad·s^{-1}/S: 17.6 D: 13.3								—	—	—
Delitto et al. (14)	1, elite weightlifter	QF	—		—	—	—	—	—	—	—	Squat/18.8	—	—

* = significant value ($P < 0.05$, but not specific from the corresponding article; ** = increase in maximal torque during the first and last PES training session for concentric and eccentric actions.
† CMJ = counter movement jump; D = dynamic or concurrent application; D² = latissimus dorsi m.; D+isom = concurrent application with an isometric action; D+conc = concurrent application with a concentric action; D+exc = concurrent application with an eccentric action; EF = elbow flexors; IPT = isokinetic peak torque; M = muscular group; MCSA = muscle cross-sectional area; MDS = maximal dynamic strength; MIS = maximal isometric strength; QF = quadriceps femoris m.; S = static or isometric application; TS = triceps surae m.

jumping achievement (with SSC), PES training exercises should be accompanied by a technical workout (i.e., plyometric) as a complement to facilitate the effects of the enhancement in maximum strength on the explosive strength required to perform the vertical jump.

Other Tests of Functional Nature. Only 3 of the studies that have been surveyed have assessed the effects of PES training by means of tests of functional nature different from the vertical jump (32, 57, 84). Wolf et al. (84) applied PES during the ascent phase of the squat exercise on a group of subjects in medium physical condition and found a significant decrease in the time needed to perform the 25-yard dash. And, on the one hand, Pichon et al. (57) assessed the influence of 3 weeks of PES training on the latissimus dorsi m. of a group of competitive swimmers by measuring the swimming time for 25-m (performed with the arms only, a pull-boy held between the thighs and a belt fastened to the ankles) and 50-m (whole stroke freestyle) distances. From this study, there are 4 points worth mentioning. First, significant improvements were observed for the 25-m distance (14.34 vs. 14.15 seconds, $p < 0.05$), as well as for the 50-m distance (26.19 vs. 25.82 seconds, $p < 0.05$). Second, improvements were observed in the stroke rate, even though an increase in the stroke length (0.05 m·cycle^{-1}) was found. Third, all individuals in the sample were sprinters or 50-m or 100-m freestyle specialists. Fourth, during the experimental phase, the subjects performed their usual training sessions. On the other hand, Herrero et al. (32) applied a PES treatment statically on the QF of 10 physical education students and did not obtain significant enhancement in the time needed to cover 20 m. It must be remembered that, among other factors (i.e., type of sample selected), the subjects did not perform any other sporting activity during the experimental phase. Therefore, improvement of the intermuscular coordination was prevented, a process which is implied in the performance of functional tests such as running or jumping (8).

Conclusions

To summarize, the PES training method can be used to enhance the contractile qualities of muscle under isometric and dynamic conditions in healthy subjects. The researches surveyed confirm that brief periods of PES have beneficial effects on muscle strength (Table 2). The heterogeneity in the magnitude of the improvements observed is mainly due to the inadequate standardization of experimental procedures (i.e., differing stimulation methods, training and testing protocols, pretraining status, and interindividual variation).

The use of PES in conditioning athletes has been argued on the basis of 2 lines of reasoning (18). First is the concept that fast-twitch fibers are preferentially stimulated by PES (Table 1). Second, inhibitory influences that are present during maximal voluntary efforts are absent during the application of PES (15, 61). Thus, PES can provide a more intense contraction to the muscle that is stimulated, and thereby induce greater adaptive responses than voluntary training (15, 53). This might be especially favorable during the concurrent application of PES in eccentric muscular actions (17, 61, 67, 80). Therefore, it has been shown that by superimposing PES, eccentric torque could be increased by an average of 21–24% above the voluntary level ($p < 0.05$; 80). In this sense, Dudley and Stevenson (18) have suggested that because the in-

tensity of training is an important factor in inducing adaptive responses to strength and power training, the concurrent application of PES during eccentric actions warrants consideration as a training method for competitive athletes.

However, there is a consensus that the force increases induced by PES training are similar to, but no greater than, those induced by voluntary training. Although in some studies (14, 45, 46, 48, 57), improvements have been found, this seems surprising if we take into account the use of experimental groups previously trained and periods of training that do not exceed 6 weeks. Nevertheless, none of these studies have controlled the potential placebo effects of PES (18), nor have they used experimental groups that have trained with VCs of similar intensity and duration. In that respect, we suggest that the number and the type of trained MUs may be different in these 2 procedures (Table 1). However, the relative contribution of the 2 procedures remains to be confirmed for elite athletes engaged in competitive sport practice.

Practical Applications

The strength gains obtained after PES training have been explained primarily by preferential neural adaptation of the fast-twitch MUs (12, 14, 45–47, 57, 71, 82, 83). It is known that during PES, the pattern of muscular recruitment is related to the proximity of the electrode and is spatially extended (42, 72). Under PES, therefore, spatial recruitment is linked to muscular topography, whereas with a VC, the order of recruitment of the MUs depends on their type (24, 33, 72). Therefore, from the point of view of sports performance, the greatest benefits of PES training will appear in those muscle groups with a higher proportion of fast MUs on their surface (24, 33), which is the case with the QF (44).

Generally speaking, it has been confirmed that the PES training method appears to be an important complement to voluntary training, because the application of PES: (a) causes an unconventional spatial recruitment of MUs that, depending on the muscular topography, may cause the preferential recruitment of the fast-twitch MUs (24, 33, 72); (b) causes an overrated metabolic demand for the required force development (59, 73, 74), causing anaerobic ATP cost to be higher for electrically induced exercise than for voluntary exercise (59, 74); (c) provides a more intense muscle-specific tension during eccentric actions than during voluntary efforts (80) and thereby induces greater adaptive responses (18, 61, 67); (d) is not specific to develop elastic behavior of skeletal muscle (45, 46); and (e) must be accompanied by technical exercises in which the athletes may practice with their changed neuromuscular system (8, 46).

References

1. Adams, G.R., R.T. Harris, D. Woodard, and G.A. Dudley. Mapping of electrical muscle stimulation using MRI. *J. Appl. Physiol.* 74:532–537. 1993.
2. Andersen, J.L., H. Klitgaard, and B. Saltin. Myosin heavy chain isoforms in single fibers from m. vastus lateralis of sprinters: influence of training. *Acta Physiol. Scand.* 151:135–142. 1994.
3. Bigard, A.X., F. Lienhard, D. Merino, B. Serrurier, and C.Y. Guezennec. Effects of surface electrostimulation on the structure and metabolic properties in monkey skeletal muscle. *Med. Sci. Sports Exerc.* 25:355–362. 1993.

4. Binder-Macleod, S.A., and L.R. McDermond. Changes in the force-frequency relationship of the human quadriceps femoris muscle following electrically and voluntarily induced fatigue. *Phys. Ther.* 72:95–104. 1991.

5. Binder-Macleod, S.A., and L. Snyder-Mackler. Muscle fatigue: clinical implications for fatigue assessment and neuromuscular electrical stimulation. *Phys. Ther.* 73:902–910. 1993.

6. Binder-Macleod, S.A., E.E. Halden, and K.A. Jungles. Effects of stimulation intensity on the physiological responses of human motor units. *Med. Sci. Sports Exerc.* 27:556–565. 1995.

7. Bircan, C., O. Senocak, O. Peker, A. Kaya, S.A. Tamci, S. Gulbahar, E. Akalin. Efficacy of two forms of electrical stimulation in increasing quadriceps strength: a randomised controlled trial. *Clin. Rehabil.* 16:194–199. 2002.

8. Bobbert, M.F., and A.J. Van Soest. Effects of muscle strengthening on vertical jump height: a simulation study. *Med. Sci. Sports Exerc.* 26:1012–1020. 1994.

9. Boobis, L.H., C. Williams, and S.A. Wotton. Human muscle metabolism during brief maximal exercise. *J. Physiol.* 338:21–22.

10. Bosco, C., I. Tarkka, and P.V. Komi. The effect of elastic energy and myoelectrical potentiation of triceps surae during stretch-shortening cycle exercises. *Int. J. Sports Med.* 3:137–140. 1982.

11. Cabric, M., H.-J. Appel, and A. Resic. Effects of electrical stimulation of different frequencies on the myonuclei and fiber size in human muscle. *Int. J. Sports Med.* 8:323–326. 1987.

12. Colson, S., A. Martin, and J. Van Hoecke. Re-examination of training effects by electrostimulation in the human elbow musculoskeletal system. *Int. J. Sports Med.* 21:281–288. 2000.

13. Coyle, E.F., D.C. Feiring, T.C. Rotkis, R.W.I.I.I. Cote, F.B. Roby, W. Lee, and J.H. Wilmore. Specificity of power improvements through slow and fast isokinetic training. *J. Appl. Physiol.* 51:1437–1442. 1981.

14. Delitto, A., M. Brown, M.J. Strube, S.J. Rose, and R.C. Lehman. Electrical stimulation of quadriceps femoris in an elite weight lifter: a single subject experiment. *Int. J. Sports Med.* 10:187–191. 1989.

15. Delitto, A., and L. Snyder-Mackler. Two theories of muscle strength augmentation using percutaneous electrical stimulation. *Phys. Ther.* 70:158–164. 1990.

16. Dudley, G.A., and R.T. Harris. Use of electrical stimulation in strength and power training. In: *Strength and Power in Sport.* P.V. Komi, ed. Oxford: Blackwell Science Ltd., 1992. pp. 329–337.

17. Dudley, G.A. and S.W. Stevenson. Use of electrical stimulation in strength and power training. In: *Strength and Power in Sport.* 2nd ed. P.V. Komi, ed. Oxford: Blackwell Science Ltd., 2003. pp. 426–435.

18. Dudley, G.A., R.T. Harris, M.R. Duvoisin, B.M. Hather, and P. Buchanan. Effect of voluntary vs. artificial activation on the relationship of muscle torque to speed. *J. Appl. Physiol.* 69:2215–2221. 1990.

19. Enoka, R.M. Muscle strength and its development: new perspectives. *Sports Med.* 6:146–168. 1988.

20. Eriksson, E., T. Haggmark, K.H. Kiessling, and J. Karlsson. Effects of electrical stimulation on human skeletal muscle. *Int. J. Sports Med.* 2:18–22. 1981.

21. Esbjörnsson, M., Y. Hellsten-Westing, P.D. Balson, B. Sjödin, and E. Jansson. Muscle fibre type changes with sprint training: effects of training pattern. *Acta Physiol. Scand.* 149:245–246. 1993.

22. Fang, Z.P., and J.T. Mortimer. A method to effect physiological recruitment order in electrically activated muscle. *IEEE Trans. Biomed. Eng.* 38:175–179. 1991.

23. Fahey, T.D., M. Harvey, R.V. Schroeder, and F. Ferguson. Influence of sex differences and knee joint position on electrical stimulation-modulated strength increases. *Med. Sci. Sports Exerc.* 17:144–147. 1985.

24. Feiereisen, P., J. Duchateau, and K. Hainaut. Motor unit recruitment order during voluntary and electrically induced contractions in the tibialis anterior. *Exp. Brain Res.* 114:117–123. 1997.

25. Friden, J. Changes in human skeletal muscle induced by long-term eccentric exercise. *Cell. Tissue Res.* 236:365–372. 1984.

26. Froese, E.A., and M.E. Houston. Torque-velocity characteristics and muscle fiber type in human vastus lateralis. *J. Appl. Physiol.* 59:309–314. 1985.

27. Garnett, R., and J.A. Stephens. Changes in the recruitment threshold of motor units produced by cutaneous stimulation in man. *J. Physiol.* 311:463–473. 1981.

28. Gorman, P.H., and J.T. Mortimer. The effect of stimulus parameters on the recruitment characteristics of direct nerve stimulation. *IEEE Trans. Biomed. Eng.* 30:407–414. 1983.

29. Hainaut, K., and J. Duchateau. Neuromuscular electrical stimulation and voluntary exercise. *Sports Med.* 14:100–113. 1992.

30. Hakkinen, K., A. Pakarinen, M. Alen, H. Kauhanen, and P.V. Komi. Neuromuscular and hormonal adaptation in athletes to strength training in two years. *J. Appl. Physiol.* 65:2406–2412. 1988.

31. Henriksson-Larsen, K., J. Friden, and M.L. Wretling. Distribution of fibre sizes in human skeletal muscle. An enzyme histochemical study in m. tibialis anterior. *Acta Physiol. Scand.* 123:171–177. (1985).

32. Herrero, A.; V. Sabio, B. Blanco, G. Cuadrado, J.G. Villa, and J. García. Valoración biomecánica de los efectos de un programa de electroestimulación en estudiantes de educación física. In: *Nuevas Aportaciones al Estudio de la Actividad Física y el Deporte.* J.F. Campo, S. Llana, and R. Aranda, eds. Valencia: Universitat de Valencia, 2001. pp. 253–264.

33. Heyters, M., A. Carpentier, J. Duchateau, and K. Hainaut. Twitch analysis as an approach to motor unit activation during electrical stimulation. *Can. J. Appl. Physiol.* 19:451–461. 1994.

34. Hortobágyi, T., and N.J. Lambert. Influence of electrical stimulation on dynamic forces of the arm flexors in strength-trained and untrained men. *Scand. J. Med. Sci. Sports.* 2:70–75. 1992.

35. Hultman, E., M. Bergström, L.L. Spriet, and K. Söderlund. Energy metabolism and fatigue. In: *Biochemistry of Exercise VII.* A. Taylor, P. Gollnick, H. Green, C. Iunuzzo, E. Noble, G. Métivier and J. Sutton, eds. Champaign: Human Kinetics, 1990. pp. 73–92.

36. Jones, N. L., N. Mccartney, T.E. Graham, L.L. Spriet, J.M. Kowalchuk, G.J.F. Haigenshauser, and J.R. Sutton. Muscle performance and metabolism in maximal isokinetic cycling at slow and fast speeds. *J. Appl. Physiol.* 59:132–136. 1985.

37. Kandel, E.R., J.H. Schwartz, and T.M. Jessell. *Principles of Neural Science.* 4th ed. New Jersey, IL: Prentice Hall, 2000.

38. Kim, C.K., S. Strange, J. Bangsbo, and B. Saltin. Skeletal muscle perfusion in electrically induced dynamic exercise in humans. *Acta Physiol. Scand.* 153:279–287. 1995.

39. Kitai, T.A., and D.G. Sale. Specificity of joint angle in isometric training. Eur. *J. Appl. Physiol.* 58:744–748. 1989.

40. Knaflitz, M., R. Merlitti, and C.J. Deluca. Inference of motor unit recruitment order in voluntary and electrically elicited contractions. *J. Appl. Physiol.* 68:1657–1667. 1990.

41. Lake, D.A. Neuromuscular electrical stimulation. An overview and its application in the treatment of sports injuries. *Sports Med.* 13:320–336. 1992.

42. Lambert, H., F. De Bisschop, G. De Mey, H. De Cuyper, S. Demurie, G. Vanderstraeten, and W. Blonde. Calculation of electric current distribution in tissue. *Eur. J. Phys. Ther.* 1:123–132. 1991.

43. Laughlin, M.H., R.J. Korthuis, D.J. Duncker, and R.J. Bache. Control of blood flow to cardiac and skeletal muscle during exercise. In: *Handbook of Physiology, Section 12: Exercise: Regulation and Integration of Multiple Systems.* L.B. Rowell and J.T. Shepherd, eds. New York: Oxford University Press, 1996. pp. 705–769.

44. Lexell, J., K. Henriksson-Larsen, and M. Sjöström. Distribution of different fibre types in human skeletal muscles. *Acta Physiol. Scand.* 177:115–122. 1983.

45. Maffiuletti, N.A., G. Cometti, I.G. Amiridis, A. Martin, M. Pousson, and J.-C. Chatard. The effects of electromyostimu-

lation training and basketball practice on muscle strength and jumping ability. *Int. J. Sports Med.* 21:437–443. 2000.

46. MAFFIULETTI, N.A., S. DUGNANI, M. FOLZ, E. DI PIERNO, AND F. MAURO. Effect of combined electrostimulation and plyometric training on vertical jump height. *Med. Sci. Sports Exerc.* 34:1638–1644. 2002.

47. MAFFIULETTI, N.A., M. PENSINI, AND A. MARTIN. Activation of human plantar flexor muscles increases after electromyostimulation training. *J. Appl Physiol.* 92:1383–1392. 2002.

48. MARTIN, L., G. COMETTI, M. POUSSON, AND B. MORLON. The influence of electrostimulation on mechanical and morphological characteristics of the triceps surae. *J. Sports Sci.* 12:377–381. 1994.

49. MATHESON, G.O., R.J. DUNLOP, D.C. MCKENZIE, C.F. SMITH, P.S. ALLEN. Forcer output and energy metabolism during neuromuscular electrical stimulation: a P-NMR study. *Scand. J. Rehab. Med.* 29:175–180. 1997.

50. MATHESON, G.O., D.C. MCKENZIE, D. GHEORGHIU, D.C. ELLINGER, H.A. QUINNEY, AND P.S. ALLEN. 31P NMR of electrically stimulated rectus femoris muscle: an in vivo graded exercise model. *Magn. Reson. Med.* 26:60–70. 1992.

51. METZGER, J.M., AND R.H. FITTS. Fatigue from high- and low-frequency muscle stimulation: contractile and biochemical alterations. *J. Appl. Physiol.* 62:2075–2082. 1987.

52. MILLER, B.F., K.G. GRUBEN, AND B.J. MORGAN. Circulatory responses to voluntary and electrically induced muscle contractions in humans. *Phys. Ther.* 80:52–59. 2000.

53. MILLER, C., AND C. THÉPAUT-MATHIEU. Strength training by electrostimulation conditions for efficacy. *Int. J. Sports Med.* 14:20–28. 1993.

54. MORITANI, T., AND H.A. DEVRIES. Neural factors versus hypertrophy in the time course of muscle strength gain. *Am. J. Phys. Med.* 58:115–130. 1979.

55. NARDONE, A., AND M. SCHIEPATTI. Shift of activity from slow to fast muscle during voluntary lengthening contractions of the triceps surae muscles in humans. *J. Physiol.* 395:363–381. 1988.

56. PÉREZ, M., A. LUCÍA, J.L.L. RIVERO, A.L. SERRANO, J.A.L. CALBET, M.A. DELGADO, AND J.L. CHICHARRO. Effects of transcutaneous short-term electrical stimulation on M. vastus lateralis characteristics of healthy young men. *Pflugers Arch.* 443:866–874. 2002.

57. PICHON, F., CHATARD, J.C., MARTIN, A., AND G. COMETTI. Electrical stimulation and swimming performance. *Med. Sci. Sports Exerc.* 27:1671–1676. 1995.

58. PORTMANN, M., AND R. MONTPETIT. Effects of training by static and dynamic electrical stimulation of the muscular contraction. *Sci. Sports.* 6:193–203. 1991.

59. RATKEVICIUS, A., M. MIZUNO, E. POVILONIS, AND B. QUISTORFF. Energy metabolism of the gastrocnemius and soleus muscles during isometric voluntary and electrically induced contractions in man. *J. Physiol.* 507.2:593–602. 1998.

60. RICH, N. Strength training via high frequency electrical stimulation. *J. Sports Med. Phys. Fitness.* 32:19–25. 1992.

61. RUTHER, C.L., C.L. GOLDEN, R.T. HARRIS, AND G.A. DUDLEY. Hypertrophy, resistance training, and the nature of skeletal muscle activation. *J. Strength Cond. Res.* 9:155–159. 1995.

62. SALTIN, B., S. STRANGE, J. BANGSBO, C.K. KIM, M. DUVOISIN, A. HARGENS, AND P.D. GOLLNICK. Central and peripheral cardiovascular adaptations to electrically induced and voluntary exercise. In: *Proceedings of the 4th European Symposium for Life Science Research Space.* ESA SP-307, 1990. pp. 591–595.

63. SELKOWITZ, D.M. High frequency electrical stimulation in muscle strengthening. A review and discussion. *Am. J. Sports. Med.* 17:103–111. 1989.

64. SINACORE, D.R., A. DELITTO, D.S. KING, AND S.J. ROSE. Type II fiber activation with electrical stimulation: a preliminary report. *Phys. Ther.* 70:416–422. 1990.

65. SINGER, B. Functional electrical stimulation of the extremities in the neurological patient: a brief review. *Aust. J. Physiother.* 33:33–42. 1986.

66. SÖDERLUND, K., P.L. GREENHAFF, AND E. HULTMAN. Energy metabolism in type I and type II human muscle fibres during short term electrical stimulation at different frequencies. *Acta Physiol. Scand.* 144:15–22. 1992.

67. STEVENSON, S.W. AND G.A. DUDLEY. Dietary creatine supplementation and muscular adaptation to resistive overload. *Med. Sci. Sports Exerc.* 33:1304–1310. 2001.

68. ST. PIERRE, D., A. TAYLOR, M. LAVOIE, W. SELLERS, AND Y. KOTS. Effects of 2500 Hz sinusoidal current on fiber area and strength of the quadriceps femoris. *J. Sports Med.* 26:60–66. 1986.

69. TAILLEFER, F. Évolution de limpulsion verticale aù cours de différents types d'entraînements par électrostimulation. Doctoral thesis, Université de Montréal. 1996.

70. TRIMBLE, M.H., AND R.M. ENOKA. Mechanisms underlying the training effects associated with neuromuscular electrical stimulation. *Phys. Ther.* 71:273–280. 1991.

71. TUROSTOWSKI, I., G. COMETTI, AND M. CORDANO. Influence of electrostimulation on human quadriceps femoris muscle strength and muscle mass. In: Proc. 10th Symp. ISBS. 1992. pp. 139–141.

72. VANDERTHOMMEN, M., J.C. DEPRESSEUX, L. DAUCHAT, C. DEGUELDRE, J.L. CROISIER, AND J.M. CRIELAARD. Blood flow variation in human muscle during electrically stimulated exercise bouts. *Arch. Phys. Med. Rehabil.* 83:936–941. 2002.

73. VANDERTHOMMEN, M., J.C. DEPRESSEUX, P. BAUVIR, C. DEGUELDRE, G. DELFIORE, J.M. PETERS, F. SLUSE, AND J.M. CRIELAARD. A positron emission tomography study of voluntarily and electrically contracted human quadriceps. *Muscle Nerve.* 20:505–507. 1997.

74. VANDERTHOMMEN, M., R. GILLES, P. CARLIER, F. CIANCABILLA, O. ZAHLAN, F. SLUSE, AND J.M. CRIELAARD. Human muscle energetics during voluntary and electrically induced isometric contractions as measured by 31PNMR spectroscopy. *Int. J. Sports Med.* 20:279–283. 1999.

75. VANDERTHOMMEN, M., B. KELLETER, J.M. CRIELAARD. Détermination de la fréquence de stimulation produisant la contraction tétanique maximale du quadriceps fémoral. In: *Electrostimulation des Nerfs et des Muscles.* J. Pelissier and C.F. Roques, eds. Paris: Masson, 1992. pp. 33–37.

76. VAN GHELUWE, C., AND J. DUCHATEAU. Effets de la superposition de lélectrostimulation à lactivité volontaire au cours dun renforcement musculaire en mode isocinétique. *Ann. Kinésithé.* 24:267–274. 1997.

77. VENABLE, M.P., M.A. COLLINS, H.S. O'BRIANT, C.R. DENEGAR, M.J. SEDIVEC, AND G. ALON. Effect of supplemental electrical stimulation on the development of strength, vertical jump performance and power. *J. Appl. Sport Sci. Res.* 5:139–143. 1991.

78. WALKER, D.C., D.P. CURRIER, AND A.J. THRELKELD. Effects of high voltage pulsed electrical stimulation on blood flow. *Phys. Ther.* 68:481–485. 1988.

79. WARD, A.R., AND N. SHKURATOVA. Russian electrical stimulation: the early experiments. *Phys. Ther.* 82:1019–1030. 2002.

80. WESTING, S.H., J.Y. SEGER, AND A. THORSTENSSON. Effects of electrical stimulation on eccentric and concentric torque-velocity relationships during knee extension in man. *Acta. Physiol. Scand.* 140:17–22. 1990.

81. WIGERSTAD-LOSSING, I., G. GRIMBY, T. JONSSON, B. MORELLI, L. PETERSON, AND P. RENSTRÖM. Effects of electrical muscle stimulation combined with voluntary contractions after knee ligament surgery. *Med. Sci. Sports Exerc.* 20:93–98. 1988.

82. WILLOUGHBY, D., AND S. SIMPSON. The effects of combined electromyostimulation and dynamic muscular contractions on the strength of college basketball players. *J. Strength Cond. Res.* 10:40–44. 1996.

83. WILLOUGHBY, D., AND S. SIMPSON. Supplemental EMS and dynamic weight training: effects on knee extensor strength and vertical jump of female college track & field athletes. *J. Strength Cond. Res.* 12:131–137. 1998.

84. WOLF, S.L., G.B. ARIEL, D. SAAR, M.A. PENNY, AND P. RAILEY. The effect of muscle stimulation during resistive training on performance parameters. *Am. J. Sports. Med.* 14:18–23. 1986.

Address correspondence to Dr. Juan José González Badillo, jjbadi@arrakis.es.