Perspective

# Russian Electrical Stimulation: The Early Experiments

Russian forms of electrical stimulation became popular to a large extent as a result of the activities of Kots, who claimed force gains of up to 40% in elite athletes as a result of what was then a new form of stimulation. He did not provide details of his published work, nor did he give references. Russian electrical stimulation became popular despite the lack of research in the English-language literature. No studies published in English examined whether the "10/50/10" treatment regimen (10 seconds of stimulation followed by 50 seconds rest, repeated for 10 minutes) advocated by Kots is optimal, and only one study addressed whether maximum muscle torque was produced at an alternating current frequency of 2.5 kHz. The few studies that compared low-frequency monophasic pulsed current and Russian electrical stimulation are inconclusive. This article reviews and provides details of the original studies by Kots and co-workers. The authors contend that these studies laid the foundations for the use of Russian forms of electrical stimulation in physical therapy. The authors conclude that there are data in the Russian-language literature that support the use of Russian electrical stimulation but that some questions remain unanswered. [Ward AR, Shkuratova N. Russian electrical stimulation: the early experiments. *Phys Ther.* 2002;82:1019–1030.]

**Key Words:** *Alternating current, Electrical stimulation, Kilohertz frequencies, Transcutaneous electrical stimulation.*

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## Introduction

Electrical stimulation is used extensively in physical therapy, and "Russian currents" have been advocated for use in increasing muscle force.[1,2] This form of electrical stimulation seems to us to be the least understood in terms of physiological effects. Russian currents are alternating currents (AC) at a frequency of 2.5 kHz that are burst modulated at a frequency of 50 Hz with a 50% duty cycle. The stimulus is applied for a 10-second "on" period followed by a 50-second "off" or rest period, with a recommended treatment time of 10 minutes per stimulation session.[1] This stimulation regimen (called the "10/50/10" regimen), applied once daily over a period of weeks, has been claimed to result in force gains, but many of the claims appear to be anecdotal.[3]

Selkowitz[1] has reviewed the experimental evidence in the English-language literature for increasing muscle force by use of Russian electrical stimulation. He concluded that there is convincing evidence for increased muscle force, but little evidence that the force gains were greater than those produced by voluntary exercise or a combination of exercise and electrical stimulation. He also noted that the studies he reviewed may not have had sufficient statistical power to distinguish among the conditions that were compared. Selkowitz also contended that there is insufficient evidence to distinguish force enhancements produced using Russian electrical stimulation ("kilohertz-frequency" AC) from those produced by other forms of electrical stimulation (eg, low-frequency monophasic pulsed current [PC]).

Only a few studies[4–10] of a relevant nature have been published since the review by Selkowitz.[1] Delitto et al[4] reported a single-subject experiment using an elite weight lifter undergoing ongoing weight training who was given periods of Russian electrical stimulation during the course of training. Marked improvements in performance, over and above those measured as a result of the training, accompanied the periods of stimulation. Delitto et al[5] compared force gains produced by Russian electrical stimulation with gains produced using voluntary exercise following anterior cruciate ligament surgery. The electrically stimulated group showed higher force gains than the group that received voluntary exercise. Subsequent studies[6,7] of force recovery following anterior cruciate ligament surgery confirmed the earlier findings and established a correlation between training intensity and amount of force recovery. One of the studies[6] also demonstrated that clinical (Russian) stimulators were more effective than portable, battery-powered (monophasic PC) units. Unfortunately, the researchers could not establish whether the difference was due to the current type or to the inability of the battery-powered unit to supply the needed current intensity for all subjects. Snyder-Mackler et al[8] compared the maximum electrically induced torque (EIT) of 3 stimulators: a Russian current stimulator, an interferential stimulator operating at a frequency of 4 kHz, and a low-frequency biphasic PC stimulator. The interferential stimulator produced less torque than the other 2 machines, but this may have been because its maximum current output was not high enough for all subjects. The highest average torque was produced by the Russian stimulator, but the difference between it and the low-frequency stimulator was not significant. Laufer et al[9] compared maximum EITs obtained using 50-Hz modulated 2.5-kHz AC, 50-Hz monophasic PC, and 50-Hz biphasic PC. The only difference found was between the biphasic PC and the 2.5-kHz AC, with the biphasic PC producing the higher torque. Ward and Robertson[10] used 50-Hz modulated currents and measured maximum EIT at different kilohertz frequencies in the range of 1 to 15 kHz. Maximum EITs were produced with a 1-kHz current. There were no comparisons with low-frequency monophasic PC.

***Experiments by Russian scientist Yakov Kots and co-workers laid the foundation for the use of "Russian currents" in physical therapy.***

Our purpose in this article is not to re-evaluate the evidence of trials that have examined force gains using Russian electrical stimulation. The review by Selkowitz[1] remains relevant, and the later studies, while adding to

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Dr Ward provided concept/idea for this work. Both authors provided writing, data collection and analysis, and consultation (including review of manuscript before submission). Ms Shkuratova provided translation of original Russian-language publications. The authors are indebted to Dr Aneta Stefanovska of the University of Ljubljana for helpful discussion of Kots' work and for providing a draft manuscript by Professor Luigi Divieti of the Polytechnic Institute of Milan that provided links to the original Russian-language publications of Kots and co-workers.

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our knowledge, do not contradict his conclusions. Our aim is to present and examine the pioneering work that was published in Russian[11,12] and that we believe laid the foundation for the clinical use of Russian electrical stimulation. The combination of the English-language studies and the earlier Russian work provides what we believe is compelling evidence for "Russian stimulation." Questions remain, however, as to whether, and to what extent, "Russian currents" may be more effective than low-frequency PC for increasing a muscle's force-generating capability.

We believe some of the popularity of Russian electrical stimulation stemmed from a talk given by Russian scientist Dr Yakov Kots[13] at a conference in 1977. Kots is reported to have advocated a stimulus regimen for increasing muscle force that he claimed was able to increase the maximum voluntary contraction (MVC) of elite athletes by up to 40%. Unfortunately, the only details of Kots' work were brief conference notes, translated from Russian and not readily accessible.[13] Selkowitz[1] noted that this is secondhand and undocumented information. Other authors (in the studies reviewed by Selkowitz[1]) have quoted the same secondary source.

Dr Kots later participated in a Canadian study on the effects of Russian electrical stimulation. College students who were athletes were the subjects.[14] The results of the study were published in English. Kots was, as best we can determine, advised by his accompanying translator that he could not provide copies of his prior Russian-language published work, nor references, to his western counterparts (Taylor AW, personal communication). The article about the Canadian study,[14] in which Kots was a coauthor, contains no references to his previously published Russian work. We find this puzzling and difficult to explain. The British Library had at the time of the Canadian study, and still has, subscriptions to the Russian-language journals in which Kots published. The details of Kots' research were readily available, albeit printed in the Russian language and located in the United Kingdom. Nonetheless, a cloak of secrecy seems to have been invoked.

In this article, we describe, in some detail, the contents of 2 key Russian-language publications[11,12] that provide the original research on which "Russian currents" are based. They were obtained from the British Library and translated by one of the authors (NS).

### *The "10/50/10" Treatment Regimen*

Russian electrical stimulation is applied for a 10-second "on" period followed by a 50-second "off" period, with a recommended treatment time of 10 minutes per stimulation session. The objective is to increase a muscle's ability to generate force, but what is often ignored is Kots' recommendation that this form of electrical stimulation should be used as an adjunct to exercise,[11] rather than as an alternative to exercise, and with electrical stimulation sessions separate from bouts of voluntary exercise.

Kots' argument for the use of electrical stimulation combined with voluntary exercise was that the commonly used exercise programs (those used at the time) build muscle bulk and muscle force but ignore the role of skill and fine motor control in athletic performance.[11] Electrical stimulation, however, preferentially recruits the fast-twitch, fast-fatiguable motor units associated with sudden, rapid movement, precise motor control, and gracefulness of movement. Thus, Kots argued, by a combination of exercise and electrical stimulation, an optimal force-enhancing regimen can be effected—one that maintains athletic skills and coordination in line with increases in muscle force. Although Kots' claim of preferential recruitment by electrical stimulation is well documented,[15] as is the involvement of fast-twitch fibers in rapid or correctional movement,[16] the claims regarding gracefulness, athletic skill, and coordination are more open to question.

Kots and Xvilon[11] reported a 2-part study, not using 2.5-kHz AC, but rather using short-duration (1-millisecond) rectangular PC at a frequency of 50 Hz. In the first part of their study, they determined optimum "on" and "off" times for stimulation. Their findings provide the rationale for the "10/50/10" treatment regimen that is characteristic of treatment with Russian electrical stimulation. In the second part of their study, they examined the force-enhancing effect of a single 10-minute training session done daily or every second day for a period of 9 or 19 days.

For the study by Kots and Xvilon,[11] 37 young athletes (age range=15–17 years, no mean or standard deviation given) were recruited and divided into 4 groups. Three groups received electrical stimulation of the biceps brachii muscle, and the fourth group received electrical stimulation of the triceps surae muscle. Current was applied using 4- × 4-cm metal electrodes over the muscle belly, with a saline-soaked pad between the electrodes and the skin. Stimulation was applied while the arm or leg was secured in an apparatus built for measuring isometric torque (Fig. 1). The apparatus was used to measure maximum EIT and MVCs. Muscle hardness also was measured for the groups that received electrical stimulation of the biceps brachii muscle, both during MVCs and during electrical stimulation. The device for measuring muscle hardness was not described in any detail. It was a skin-mounted device (Fig. 1b) that, we surmise, applied a controlled force to the skin surface and gave a "hardness" reading determined by the

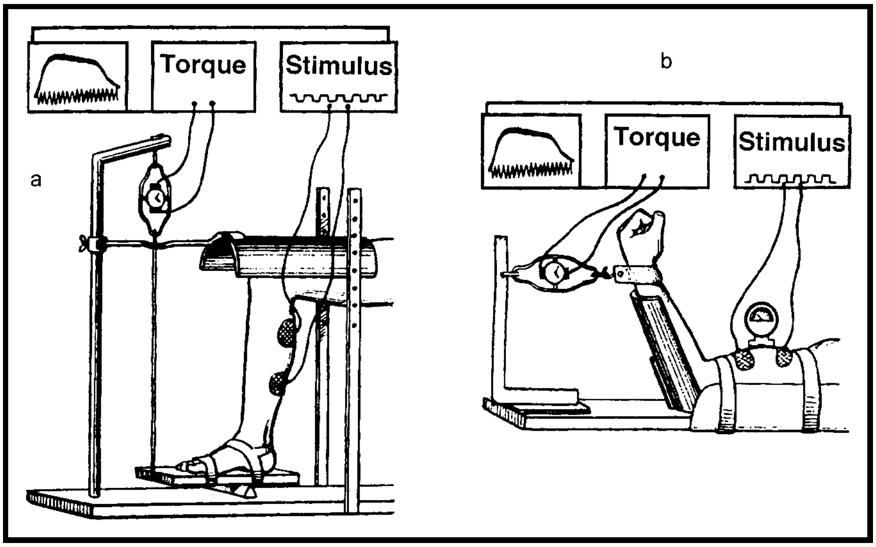


**Figure 1.**
Apparatus used for measurement of maximum voluntary contraction and maximum electronically induced torque of (a) triceps surae muscles and (b) biceps brachii muscles. A skin-surface–mounted device was used to measure the hardness of the biceps brachii muscles. Reproduced from Kots and Xvilon.[11]

amount of indentation produced. Hardness, measured in this way, would give an indirect indication of muscle force but, we believe, would give readings that are unduly biased in favor of the part of the muscle closest to the measuring device.

For the first part of the study by Kots and Xvilon,[11] trains of 50-Hz pulses were applied at maximum tolerable intensity for 15 seconds, and the evoked muscle torque and stimulus intensity were monitored. Kots and Xvilon found no appreciable decrease in torque with trains of up to 10 seconds' duration. *Electrically induced fatigue*, defined as a visible decline in the torque record, was noted (Fig. 2a) at a mean of 12.5 seconds (SD=1.8), after which it progressed rapidly. Fatigue was not quantified but simply rated as present or absent. On the basis of their observations, Kots and Xvilon concluded that a maximum "on" time of 10 seconds was desirable to avoid fatigue during the pulse train.

Having settled on a 10-second "on" time, Kots and Xvilon[11] then established what "off" time was required to avoid fatigue between pulse trains. Fatigue, in this case, was defined as a visible decrease in torque between 2 consecutive 10-second stimulus trains. They compared "off" times of 10, 20, 30, 40, and 50 seconds and reported that with "off" times of 30 seconds or less (Fig. 2b), the average torque during the second train was less than the torque during the first train and that fatigue increased (torque declined) during the second 10-second train. They concluded that the "off" time needed to be 40 to 50 seconds. They then measured the torque variation over 10 consecutive 10-second trains and found that with a 40-second "off" time, signs of fatigue were evident, particularly in the last few trains. With a 50-second "off" period, no fatigue was evident over the 10 consecutive trains (Fig. 2c). Accordingly, they chose a nonfatiguing "10/50/10" (10 seconds "on" and 50 seconds "off" for 10 trains) protocol for the second part of their study.

### *Increasing Muscle Force Using the "10/50/10" Treatment Regimen*

In the second part of their study, Kots and Xvilon[11] used a single "10/50/10" treatment applied once daily or on every second day, and they monitored changes in muscle torque and muscle hardness over 9 or 19 days. Before each stimulation session, muscle torque and muscle hardness were measured during each of 3 MVCs. Limb circumference was measured during each MVC and after every MVC with the subject relaxed. Electrically induced torque and applied current also were monitored during treatment. Table 1 provides details of the 4 series of tests.

Kots and Xvilon[11] noted that although their EIT values were only a fraction of MVC, muscle hardness, as measured by their indentation device, was always greater than that of an MVC (Tab. 1). Their conclusion, based on their hardness measurements, was that electrical stimulation produces greater force in the excited muscle than when recruited voluntarily. The greater MVC values, they suggested, were due to (automatic voluntary) recruitment of synergistic muscles, which were not recruited electrically. That is, MVC measurements reflect the net effect of all synergistic muscles contributing to a contraction. Hardness values reflect the contribution of just the muscle directly under the measuring device.

Kots and Xvilon[11] further observed that their subjects tolerated progressively higher stimulus intensities over the 9- or 19-day training period and that there was a corresponding progressive increase in EIT. The increases are shown in Figure 3. Increases in MVC and limb circumference also were found. The findings are summarized in Table 2 and depicted graphically as part of Figure 4.

The authors[11] expressed surprise at the rapid and large increases in force production. They also noted that the magnitude of the force gain appeared to depend on the number of stimulation sessions (in Tab. 2, compare series 1 and 2 where 9 treatment sessions were used with series 3 where 19 treatments were applied). There seemed to be little difference whether the treatments were done every day (series 2 [9 sessions]) or every second day (series 1 [9 sessions]).

Figure 4 shows MVC plotted against duration in the treatment program (in days). The changes in limb circumference with the muscle relaxed and when producing an MVC also are plotted. Both circumference and MVC values are expressed as a percentage of the initial (baseline) values prior to electrical stimulation.

Kots and Xvilon[11] argued that increasing a muscle's force-generating capability can be achieved by 2 means. One means is by central nervous system (CNS) adaptation whereby a greater MVC is produced by CNS "learning" and adaptation of the pattern of excitation. In this case, the force gains are achieved by greater and more effective recruitment of muscle fibers. The second means is by building the physical bulk of the muscle to produce a greater force output for the same neural input. In this case, the muscle fibers grow in size and muscle volume increases. The increases in limb circumference (and thus, by inference, muscle bulk) paralleled the increase in muscle force, so the authors concluded that the force gains were predominantly of peripheral origin.

To establish whether the MVC testing that was part of the experimental protocol contributed to the force gains, a control group was used. These subjects performed MVCs 6 times per day for 19 days to match the experimental group, who performed 3 MVCs before each stimulation session and 3 MVCs after each stimulation session. No increase in force was produced. Although this finding demonstrates that the force gains were not a result of performing repetitive MVCs, the control group does not control for a placebo response, because there is no way the controls could be unaware of the presence or absence of electrical stimulation. Given that few of the later studies by a variety of authors showed such large force gains with stimulation sessions so few and short, we question whether the extreme motivation for the young Russian athletes was a factor in the force gains. Possibly the age of the subjects had a bearing on the outcome. Other studies (reviewed by Selkowitz[1]) used subjects who were more physically mature and less motivated.

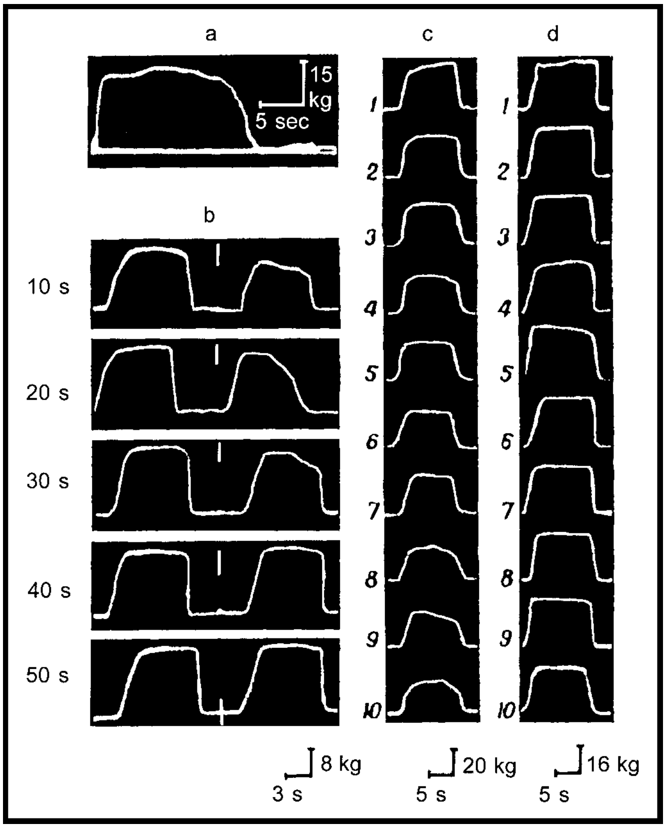


**Figure 2.**
Electrically induced torque using different stimulus regimens: (a) 50-Hz pulses applied at maximum tolerable intensity for 15 seconds, (b) two 10-second trains applied with rest periods of 10 to 50 seconds between trains, (c) 10 consecutive trains of stimuli applied using the "10/50/10" treatment regimen at different target stimulation intensities. Reproduced from Kots and Xvilon.[11]

### *Medium-Frequency Alternating Current*

Andrianova et al[12] reported on the use of kilohertz-frequency sinusoidal alternating current for increasing a muscle's force-generating capability. Both continuous (unmodulated) AC and AC bursts, modulated at 50 Hz (10 milliseconds "on" and 10 milliseconds "off"), were used. Andrianova and colleagues examined "direct" stimulation, where the electrodes were placed over the muscle, and "indirect" stimulation, where they attempted to stimulate the nerve trunk supplying the muscle. Their article[12] reports a 4-part study involving either wrist and finger flexors or the calf muscles, or both. For direct stimulation of wrist and finger flexors, electrodes measuring 6 × 3 cm and 4 × 3 cm were applied to the palmar surface of the forearm, with the long side across the forearm and the larger electrode more proximal. For indirect stimulation, a thin electrode (2.5 × 0.5 cm) was positioned along the fissure of the elbow joint and a larger electrode (3 × 1.5 cm or 3.5 × 1 cm, respectively) was positioned on the palmar surface of the forearm or on the inner surface of the shoulder (long side across the inner surface). No further details of electrode placement were given. The authors stated that the same size electrodes were used for the calf muscles, but no details of electrode placement were given. It is uncertain, therefore, how electrodes were located to activate the nerve trunk supplying the calf

**Table 1.**
Details of the Four Series of Trials Conducted by Kots and Xvilon[11] Using the "10/50/10" Treatment Regimen[a]

| Variable | Series 1 | Series 2 | Series 3 | Series 4 |
|---|---|---|---|---|
| No. of subjects | 11 | 10 | 8 | 8 |
| Age (y) | 15–16 | 15–16 | 16–17 | 16–17 |
| Muscle | Biceps brachii | Biceps brachii | Biceps brachii | Triceps surae |
| Stimulation | Once every second day | Daily | Daily | Daily |
| No. of treatment sessions | 9 | 9 | 19 | 19 |
| EIT (% Of MVC) | | | | |
| $\overline{X}$ | 53.9 | 46.5 | 43.8 | 36.5 |
| SD | 2.7 | 0.7 | 1.1 | 1.9 |
| Range | 38.5–60.1 | 42.6–49.3 | 27.2–57.7 | 27.1–41.3 |
| Muscle hardness (% of MVC) | | | | |
| $\overline{X}$ | 106.4 | 108.0 | 108.0 | |
| SD | 0.4 | 0.3 | 0.5 | |
| Range | 104.0–110.0 | 105.0–111.0 | 106.0–109.0 | |

[a] EIT=electrically induced torque, MVC=maximum voluntary contraction. No mean and standard deviation values were stated for age.

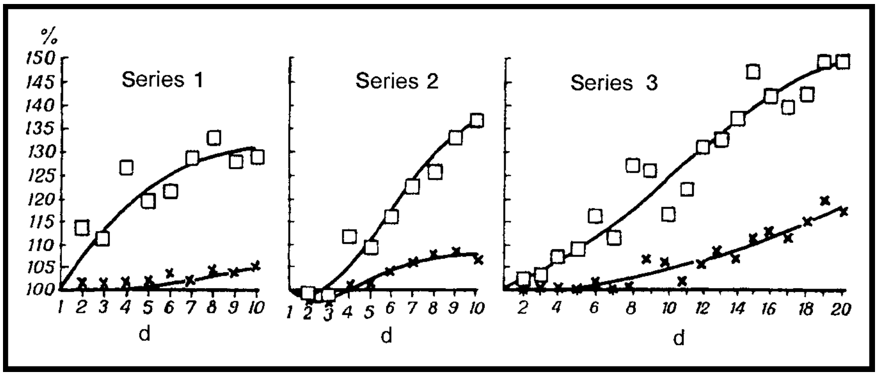


**Figure 3.**
Variation in maximum tolerable current intensity (**X**) and maximum electrically induced torque (□) for 3 of the series of tests of the "10/50/10" treatment regimen. Values are expressed as percentage of the first-trial (day 1) results. Reproduced from Kots and Xvilon.[11]

muscles. The number of subjects in each part of the study ranged from 7 to 10.

In the first part of the study reported by Andrianova et al,[12] continuous (unmodulated) AC at frequencies of 100, 500, 1,000, 2,500, and either 3,000 or 5,000 Hz was used for stimulation of the wrist and finger flexors. Motor thresholds, maximum tolerable current, and the current required to achieve 60% of the maximum EIT were measured at each frequency. The results are shown in Figure 5.

Andrianova et al[12] reported that although current levels increased with increasing frequency, the discomfort associated with the stimulation decreased. They did not state whether or how discomfort was quantified, so we conclude that this was an empirical observation. For direct stimulation of the calf muscles, a maximum force of 92.5 kg (SD=25.0), approximately 70% of MVC, was elicited at 2.5 kHz. For indirect stimulation (of wrist and finger flexors), the maximum force was elicited at 1 kHz. Above 1 kHz, rapid fatigue was noted. The authors concluded that a frequency of 1 kHz was optimal for force production using indirect stimulation and 2.5 kHz was optimal when using direct stimulation.

The second part of the study reported force measurements made using wrist and finger flexors with direct and indirect stimulation and indirect stimulation with 10-millisecond bursts at 50 Hz. Table 3 shows the maximum force produced. The results indicate that for indirect stimulation, whether continuous or modulated at 50 Hz, maximum force was produced at an AC frequency of 1 kHz. For direct stimulation using a continuous stimulus, maximum force was produced at an AC frequency of 2.5 kHz. Direct stimulation using 50-Hz bursts does not seem to have been examined.

Whether 1 kHz is the optimal frequency for indirect stimulation, whereas 2.5 kHz is the optimal frequency for direct stimulation, was investigated in the third part of the study,[12] which used wrist and finger flexors and a continuous AC stimulus. Frequencies of 2.5 kHz and 1 kHz only were compared (Tab. 4). These results were in agreement with the findings of the previous part of the

**Table 2.**
Overall Changes[a] in Maximum Voluntary Contraction (MVC) and Limb Circumference for the Four Series of Tests Reported by Kots and Xvilon[11]

| | Series 1 | | | Series 2 | | | Series 3 | | | Series 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | $\overline{X}$ | SD | Range | $\overline{X}$ | SD | Range | $\overline{X}$ | SD | Range | $\overline{X}$ | SD | Range |
| MVC force (kg) | | | | | | | | | | | | |
| Before series | 25.6 | 3.5 | 21.6–32.0 | 25.3 | 1.4 | 17.7–33.0 | 28.8 | 2.8 | 18.7–36.7 | 57.5 | 0.8 | 47.6–70.6 |
| After series | 32.5 | 0.7 | 27.6–36.3 | 32.8 | 1.5 | 23.9–39.8 | 39.9 | 2.8 | 28.9–53.6 | 89.8 | 2.0 | 62.6–108.4 |
| % change | 27.0 | 3.9 | 12.0–52.9 | 29.8 | 2.4 | 19.3–40.6 | 38.4 | 3.6 | 19.8–48.8 | 56.1 | 5.9 | 30.0–76.0 |
| Limb circumference, relaxed (cm) | | | | | | | | | | | | |
| Before series | 26.4 | 0.5 | 24.5–29.0 | 25.5 | 0.7 | 21.5–28.8 | 25.8 | 1.1 | 21.0–29.0 | 34.4 | 0.2 | 33.0–35.0 |
| After series | 27.1 | 0.4 | 26.0–31.2 | 26.4 | 0.7 | 22.3–29.8 | 26.8 | 1.1 | 21.6–29.6 | 35.8 | 0.2 | 35.0–36.0 |
| Change | 0.7 | | 0.5–1.6 | 0.9 | | 0.6–1.6 | 1.0 | | 0.5–1.3 | 1.4 | | 0.8–1.6 |
| Limb circumference, with MVC (cm) | | | | | | | | | | | | |
| Before series | 29.1 | 0.5 | 27.0–32.0 | 28.2 | 0.9 | 24.0–32.9 | 28.8 | 1.1 | 23.0–32.0 | | | |
| After series | 30.0 | 0.5 | 28.5–33.9 | 29.1 | 0.9 | 24.5–33.7 | 30.1 | 1.1 | 24.1–33.3 | | | |
| Change | 0.9 | | 0.6–2.0 | 0.9 | | 0.5–1.2 | 1.3 | | 1.0–1.7 | | | |

[a] Kots and Xvilon[11] did not report statistical analyses of their data. The group-average data shown do not permit analysis, which would require "before" and "after" data paired by subject.

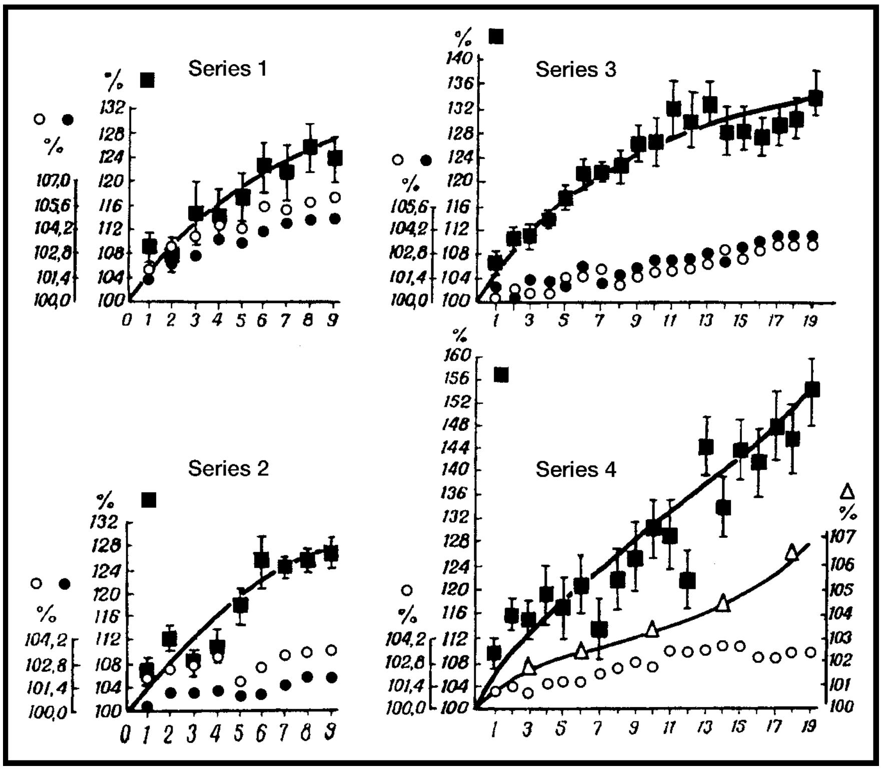


**Figure 4.**
Maximum voluntary contraction (MVC) (■), change in limb circumference with the muscle relaxed (●), and change in limb circumference when producing an MVC (○), plotted against duration in the treatment program (in days). Values are expressed as a percentage of the initial (baseline) measurements prior to electrical stimulation. Series 4 results (triceps surae muscle stimulation) show jump height (△), but not changes in relaxed limb circumference. Reproduced from Kots and Xvilon.[11]

study, although only stimulation with a continuous waveform was used in this part of the study. The authors apparently did not examine 50-Hz burst modulation.

Andrianva et al[12] noted that both indirect and direct stimulation produced similar levels of maximum force, although at different frequencies. A frequency of 1 kHz was optimal for force production using indirect stimulation and a continuous waveform, and a frequency of 2.5 kHz was optimal when using direct stimulation and a continuous waveform. The observation that levels of maximum force was similar led the authors to suggest that direct stimulation was capable of exciting not only the superficial muscle fibers but presumably also the deep muscle fibers excited by indirect (nerve trunk) stimulation.

### *50-Hz Burst Modulation*

Andrianova et al[12] concluded that whether current is applied in continuous mode or in 10-millisecond, 50-Hz bursts, the maximum force induced and the optimal frequency are not affected. This conclusion is consistent with the report of Soloviev,[17] who stated there was little difference in the variation in motor threshold with frequency, whether the current applied was continuous or burst modulated at

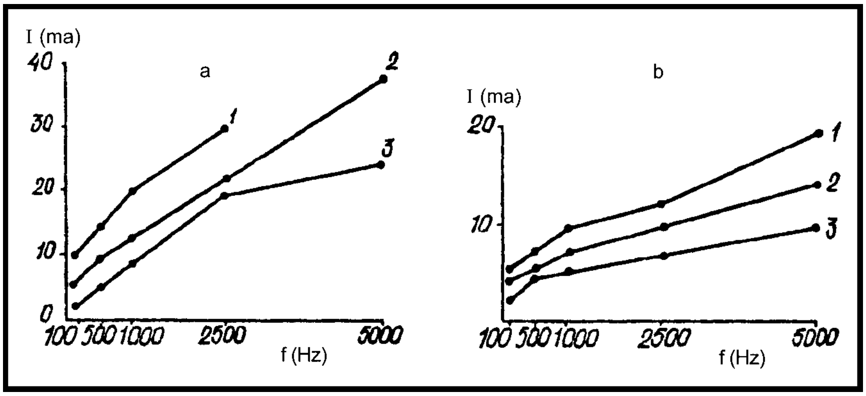


**Figure 5.**
Maximum tolerable current (1), current required to achieve 60% of the maximum electrically induced torque (2) and motor thresholds (3) measured at different alternating current frequencies in the range 100 Hz to 5 kHz using continuous alternating current. I=intensity, f=frequency. Reproduced from Andrianova et al.[12]

**Table 3.**
Maximum Force (in Kilograms, at the Pain Tolerance Threshold) With Stimulation of the Wrist and Finger Flexors at Different Alternating Current Frequencies in the Range of 100 Hz to 5 kHz[a]

| Stimulation | 100 Hz | 500 Hz | 1 kHz | 2 kHz | 3 kHz | 5 kHz |
|---|---|---|---|---|---|---|
| Direct, continuous | | | | | | |
| $\overline{X}$ | 9.6 | 16.2 | 19.5 | 23.4 | 20.2 | |
| SD | 3.1 | 4.9 | 5.0 | 5.7 | 4.4 | |
| Indirect, continuous | | | | | | |
| $\overline{X}$ | 18.6 | 21.6 | 23.5 | 18.8 | | 13.5 |
| SD | 3.7 | 6.1 | 6.2 | 6.2 | | 4.2 |
| Indirect, 50-Hz bursts | | | | | | |
| $\overline{X}$ | 22.1 | 24.4 | 25.5 | 18.7 | | 18.4 |
| SD | 4.8 | 5.4 | 4.8 | 3.8 | | 2.8 |

[a] "Direct" refers to stimulation with electrodes over the muscle belly, "indirect" refers to stimulation of the nerve trunk. From Andrianova et al.[12] Only mean and standard deviation values were given by Andrianova et al.[12] Ranges for the force values were not stated. Andrianova et al[12] did not report statistical analyses of their data. The group-average data shown do not permit analysis, which would require data across frequencies for each subject so that pair-wise comparisons could be made.

50 Hz. Accordingly, Andrianova et al recommended 50-Hz burst modulation because it would result in halving of the electrical energy delivered to the patient while producing little or no decrease in the maximum force induced. Soloviev's findings are supported by a recent study[18] in which motor thresholds in the range 1 to 25 kHz were examined. Little difference was found between a continuous stimulus and one modulated at 50 Hz.

To verify that 50-Hz burst modulation did not diminish maximum EIT, Andrianova et al[12] carried out the fourth part of their study, comparing continuous and burst-mode stimulation using direct stimulation of the calf muscles and indirect stimulation of the wrist and finger flexors. The findings are shown in Table 5. The results support the contention that 50-Hz, 50% duty cycle, burst modulation does not diminish maximum EIT. For this reason alone, they argued, burst modulation should be preferred for patient treatment because the physiological response is indistinguishable, while the current levels are halved. What does not seem to have been directly established is whether 2.5 kHz is still an optimal frequency for force production when 50-Hz bursts, rather than continuous AC, are used.

### *Increasing Muscle Force Using 50-Hz Burst Modulation*

Andrianova et al[12] reported force gains in 2 different groups of 16 young wrestlers. The first group had their calf muscles stimulated directly using a frequency of 2.5 kHz. Stimulation was once per day for 18 days. Maximum voluntary contraction, limb circumference, and jumping height were measured daily. Half of the second group had their tibialis anterior muscle stimulated directly at 2.5 kHz, and the other half of the group had their tibialis anterior muscle stimulated indirectly at 1 kHz. For both groups, the stimulation regimen was the same as that described earlier (10 seconds "on," 50 seconds "off," and 10 stimulation cycles) but with the current burst modulated at 50 Hz with a 50% duty cycle. Current was applied at a maximum tolerable level. The results are shown in Figure 6.

Force gains achieved were largest for the group that underwent calf muscle stimulation, where the increase in MVC over the 18-day training period was 45%. These force gains were accompanied by an increase in limb circumference of 3% and by an increase in jumping height of almost 15%. The group that underwent stimulation of the tibialis anterior muscle had an increase in dorsiflexor MVC of 30% or more. Indirect stimulation at 1 kHz appeared to result in a more rapid force gains than direct stimulation at 2.5 kHz (days 1–10), but by the end of the training period the difference was small.

## Discussion

### *Increasing Muscle Force*

The force gains reported by Kots and Xvilon[11] (27%–56%) and Andrianova et al[12] (30%-45%) are at the high end of gains reported in the English-language literature (7%-48%).[1] This is perhaps not surprising given the likelihood of a placebo response. Kots and co-workers had subjects who were young (15–17 years of age, no mean and standard deviation stated) and had not reached maturity and who were also in training as potential Olympic athletes. Other researchers[1] used more physically mature participants who also might have had less personal incentive to achieve force gains. Thus, the placebo effect in the studies of Kots and co-workers would be expected to be large. The extent of the placebo response is uncertain, but there is little doubt that the placebo effect can increase force measurements. It is interesting to note that in a later study,[4] in which Russian electrical stimulation was used and the subject was an elite weight lifter, the authors reported performance gains comparable to those reported by Andrianova et al.[12]

Force gains have been shown with electrical stimulation, just as they have with voluntary exercise, and there is some evidence that a combination of voluntary exercise and electrical stimulation (applied on separate occasions) can produce greater force gains than either intervention used alone.[1] A problem with the studies in which electrical stimulation was compared with voluntary exercise or a combination of both interventions is that there may not have been enough subjects to have sufficient statistical power. Although the numbers of subjects (typically between 10 and 20 per group) may have been enough to distinguish a large effect between treatment and control, the numbers appear to be too small to distinguish lesser effects that might have existed between the different treatment groups.

Nonetheless, the balance of evidence, in our opinion, suggests that a combination of exercise and electrical stimulation is more effective than either intervention used alone. There are 2 possible explanations. The first explanation is one of experimental design. With the combination applied sequentially (voluntary exercise and separate electrical stimulation), the total amount of exercise is greater. The second explanation is that exercise and electrical stimulation preferentially recruit different fiber types. Kots and Xvilon[11] argued that traditional, voluntary exercise regimens promoted increased force production in slow-twitch, fatigue-resistant muscle fibers because they are the ones first recruited in a voluntary contraction and there is limited recruitment of fast-twitch fibers in all but the fastest and most forceful voluntary contractions. An electrical stimulation regimen, by contrast, preferentially recruits the fast-twitch muscle fibers, which are innervated by larger-diameter motoneurons. On this basis, they contended, an optimal force gain program should include both exercise and electrical stimulation to increase force production of both fiber types.

**Table 4.**
Verification of the Choice of Optimal Frequencies for Direct and Indirect Stimulation of Forearm Muscles: Maximum Electrically Induced Force (in Kilograms) at 1 kHz and 2.5 kHz[a]

| Stimulation | 1 kHz $\overline{X}$ | 1 kHz SD | 2.5 kHz $\overline{X}$ | 2.5 kHz SD |
|---|---|---|---|---|
| Direct, continuous | 23.6 | 4.1 | 26.3 | 4.5 |
| Indirect, continuous | 27.7 | 7.0 | 19.8 | 5.4 |

[a] The footnote to Table 3 regarding statistical analysis is also applicable here. From Andrianova et al.[12]

**Table 5.**
Average Values of the Force Induced Through Direct Stimulation at 2.5 kHz of the Extensors and Flexors of the Foot and Indirect Stimulation at 1 kHz of the Flexors of the Hand and Fingers to Compare[a] Continuous Stimulation With 50-Hz Modulated Stimulation

| Muscle | Stimulation | Frequency (kHz) | Force (kg) $\overline{X}$ | Force (kg) SD |
|---|---|---|---|---|
| Triceps surae muscles | Direct, continuous | 2.5 | 97.5 | 14.0 |
| Triceps surae muscles | Direct, 50-Hz bursts | 2.5 | 109.2 | 10.0 |
| Wrist/finger flexors | Indirect, continuous | 1 | 33.3 | 7.2 |
| Wrist/finger flexors | Indirect, 50-Hz bursts | 1 | 32.8 | 6.2 |

[a] The footnote to Table 3 regarding statistical analysis is also applicable here.

Kots and Xvilon[11] also argued that, because of differential recruitment, muscle force-generating regimens consisting of voluntary exercise alone run the risk of an increase in muscle force production at the expense of reducing the speed of muscle contraction. They argued that fast-twitch fiber force gains should accompany voluntary contraction force gains of slow-twitch fibers in order to maintain the balance, which they believed is needed for performance of skillful, well-executed movements.

### *The "10/50/10" Stimulation Regimen*

Kots and Xvilon[11] contended that to increase force production, electrical stimulation should be nonfatiguing, meaning that there should be no decrease in force during the stimulus period. Their observations of force decline using low-frequency (50-Hz) monophasic PC with different "on" and "off" times during a 10-minute treatment period were their evidence that the "10/50/10" stimulation regimen is "nonfatiguing," provided that the stimulus is monophasic PC. Their argument for a nonfatiguing response was that further stimulation of an electrically fatigued muscle will not increase the muscle's force production capability. The argument has credibility. At a stimulus frequency of 50 Hz, the dominant fatigue mechanisms are neurotransmitter depletion and

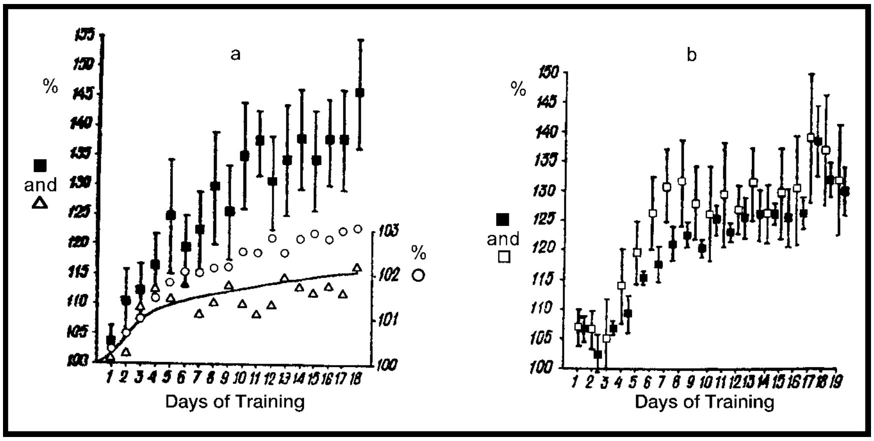


**Figure 6.**
(a) Variation in maximum voluntary contraction (MVC) (■), jumping height (△), and limb diameter (○) in response to daily stimulation of triceps surae muscles. Direct stimulation using 2.5-kHz alternating current. (b) Variation in MVC in response to daily stimulation of tibialis anterior muscle using either direct stimulation at 2.5 kHz (■, 8 subjects) or indirect stimulation at 1 kHz (□, 8 subjects). Quantities shown are expressed as percentage of initial (baseline) values. Maximum voluntary contractions are mean and standard deviation values. Currents were burst modulated at 50 Hz with a 50% duty cycle. Sixteen subjects were used in each study. Reproduced from Andrianova et al.[12]

propagation failure at the level of the t-tubule system,[19] processes that would not result in increased force production.[19,20] Fatigue induced by voluntary exercise involves much lower nerve fiber firing frequencies[20] and places greater stresses on the contractile components of the muscle fibers. Such stresses are argued to be needed for strengthening.[19] Thus, we believe that the choice of a "10/50/10" stimulation regimen to avoid neuromuscular fatigue has a sound physiological basis.

The "10/50/10" protocol was established using short-duration monophasic PC at a frequency of 50 Hz.[11] Because a "10/50/10" regimen is optimal when using short-duration PC does not mean that the same would necessarily apply when using kilohertz-frequency bursts of AC modulated at 50 Hz. Andrianova et al[12] used 50-Hz bursts of kilohertz-frequency AC and the "10/50/10" protocol, and this has led to the assumption that this protocol is optimal when using kilohertz-frequency AC. Fatigue effects were not measured by Andrianova et al,[12] and their rationale for using the protocol was simply a reference to the study by Kots and Xvilon.[11] The focus was on optimal frequencies for maximum force production. Andrianova et al[12] reported that at higher frequencies, there was a rapid drop-off in force, which limited the maximum EIT, that is, that fatigue effects appeared to have an effect at higher frequencies, but this was apparently only a qualitative observation. Their observation echoes that of Djourno,[21] who in 1952 reported the occurrence of increasing rates of fatigue with increasing frequency when using kilohertz-frequency AC and continuous stimulation. Nonetheless, fatigue seems to have been all but ignored by Andrianova et al,[12] who chose a "10/50/10" protocol for both direct and indirect stimulation on the basis of results obtained by Kots and Xvilon[11] using low-frequency monophasic PC.

Some years after the study by Andrianova et al,[12] Stefanovska and Vodovnik[22] compared 50-Hz single-pulse stimulation and 50-Hz burst stimulation at 2.5 kHz using 10-second trains of stimulation. They reported that when using 50-Hz single pulses, what they called "negligible fatigue," defined as no visible decrease in EIT, occurred over a 10-second stimulation period, even during repetitive stimulation. By contrast, the force measured using 2.5-kHz AC showed appreciable decline during the 10 seconds of stimulation. Whether a "10/50/10" protocol is optimal when using 50-Hz bursts of kilohertz-frequency AC, therefore, is questionable.

*Optimal Frequencies*

Andrianova et al[12] compared continuous stimulation with 50-Hz burst stimulation in the frequency range of 100 Hz to 5 kHz but only using what they considered indirect (presumably via the nerve trunk) stimulation. Their conclusion was that burst modulation did not affect the optimal frequency for muscle force production. Both continuous and burst-modulated waveforms produced maximum force at 1 kHz (Tab. 3). Unfortunately, no comparison of continuous and burst-modulated waveforms using direct (over the muscle) stimulation was reported. Their conclusion was that burst modulation makes no difference to the optimal frequency and should be preferred for patient treatment because the physiological response is indistinguishable while the current levels are halved. Although this was demonstrated for indirect stimulation, whether 2.5 kHz is still optimal for direct stimulation when 50-Hz burst modulation is used was not demonstrated.

Only one subsequent study of the frequency dependence of force production using kilohertz-frequency AC has been reported.[10] Ward and Robertson[10] examined frequencies in the range of 1 to 15 kHz, burst modulated at 50 Hz, and found that maximum wrist extensor torque was elicited at 1 kHz. Lower frequencies were not examined. The proximal electrode was positioned over the nerve trunk, and the distal electrode was positioned over the muscle belly, so the stimulation could not be unequivocally identified as "direct" or "indirect." The finding of maximum torque production at 1 kHz suggests that indirect stimulation under the proximal electrode contributed most to torque production.

Data suggest to us and others that an AC frequency of 2.5 kHz is optimal for direct stimulation when 50-Hz burst modulation is used, but this is inference rather than observation. We believe that it would be desirable to test the hypothesis experimentally. The evidence for 1 kHz as an optimum frequency for indirect stimulation, in our view, is more compelling (Tab. 3).

### *Kilohertz-Frequency AC Bursts or Low-Frequency Monophasic PC?*

Andrianova et al[12] stated that burst-modulated, kilohertz-frequency AC is preferable to low-frequency PC because the stimulation is more comfortable. They concluded, on the basis of their research, that the optimum frequencies for AC stimulation are 1 kHz for indirect stimulation and 2.5 kHz for direct stimulation. Their conclusions have an interesting historic basis. The ability to evoke a strong, comfortable contraction with kilohertz-frequency AC was first noted by d'Arsonval,[23] who reported, in 1891, that with continuous AC at a fixed voltage, neuromuscular excitation became stronger up to 1,250 to 1,500 Hz, remained constant to 2,500 Hz, and decreased between 2,500 and 5,000 Hz. d'Arsonval also noted that physical sensation and discomfort decreased steadily with increasing frequency up to the maximum frequency that his stimulator could produce (5,000 Hz). The idea that kilohertz-frequency AC is able to produce strong, comfortable muscle contractions at an optimal frequency between 1.5 and 2.5 kHz had been advanced by d'Arsonval about 80 years earlier than Andrianova et al.[12]

Unfortunately, d'Arsonval[23] did not report details of the electrode placement for his experiments. His interpretation of his studies indicated to him that maximum force with least discomfort is elicited between 1.5 and 2.5 kHz. In the early days of electrical stimulation of human subjects, it was common practice to use 2 cylindrical, metal, hand-held electrodes.[24] Stimulation with this technique, in our opinion, might be more like "direct" stimulation than "indirect" stimulation because the relatively bulky muscles would be positioned closer to the electrodes and would be more susceptible to direct excitation, rather than via the more distantly located, small-volume nerve trunk.

The studies reported by Ward and Robertson[10,25] shed some light on to the question of comfort of stimulation and its relation to maximum torque production. These authors[25] measured sensory, motor, and pain thresholds at different frequencies in the range 1 to 35 kHz using a 50-Hz burst-modulated stimulus. They found that the separation between motor and pain thresholds increased between 1 and 10 kHz and then decreased at higher frequencies. To the extent that separation between motor and pain thresholds is a predictor of comfort, we surmise that more comfortable contractions are produced as the frequency increases, up to an optimum frequency of 10 kHz. In a subsequent study,[10] Ward and Robertson found that maximum torque was elicited not at 10 kHz, but at 1 kHz (the lowest frequency examined). These findings call into question the relationship between comfort of stimulation (at low torque levels) and maximum EIT.

An assumption of Andrianova et al[12] was that if the stimulus is more comfortable, greater maximum force can be elicited. On this basis, they stated a preference for kilohertz-frequency AC rather than low-frequency PC. At face value, this seems to be a reasonable assumption. However, as we have contended, when comparing different frequencies, greatest comfort and maximum EIT are not at the same frequency. Thus, it does not necessarily follow that if kilohertz-frequency AC produces more comfortable contractions than low-frequency PC, greater maximal contractions will be produced.

The limited number of studies that have directly compared low-frequency PC and 2.5-kHz AC[8,9,26] are inconclusive. A recent study by Laufer et al[9] demonstrated greater EITs with low-frequency PC than 2.5-kHz AC. Walmsley et al[26] reported no difference (calling into question the statistical power of their study). Snyder-Mackler et al[8] also reported no difference, again calling into question whether the study had sufficient statistical power. Each of these groups of investigators used a stimulus that was ramped or increased manually by the experimenters, and this may have resulted in muscle fibers ceasing to contract due to neurotransmitter depletion, with a consequent underestimation of the peak torque that can be elicited using 2.5-kHz AC.[18,27]

## Conclusion

What are called "Russian currents" are widely used in physical therapy, but the support for their use in the English-language literature is scant. The studies reported in the Russian literature by Kots and Xvilon[11] and Andrianova et al[12] provide some experimental data to support their use. Andrianova et al[12] concluded that 1 kHz, rather than 2.5 kHz, is preferable for maximum force production when muscles are stimulated indirectly (over the nerve trunk), and this conclusion is supported by a more recent study.[10] This finding suggests that "Russian current" stimulators should provide a choice of 1-kHz or 2.5-kHz stimulus waveforms. As we have noted, however, the early studies[11,12] have not appeared in the English-language literature. In addition, we have no idea as to the extent to which they may have undergone peer review before publication.

The question of whether the burst-modulated AC used in "Russian current" stimulators is more effective for force production than low-frequency PC remains open. The data[8,9,26] are inconclusive. Other questions also remain. The "10/50/10" protocol that is fundamental to Russian electrical stimulation was based on measurements made using a low-frequency monophasic PC stimulus and not kilohertz-frequency AC bursts. The "10/50/10" protocol was chosen because it produced no measurable force reduction during the 10-minute stimulation period. Yet 10 seconds of 50-Hz burst-modulated, kilohertz-frequency stimulation has been shown to produce a marked reduction in force.[22] There is a question as to whether the "10/50/10" regimen is still optimal when kilohertz-frequency AC is used. The force gains measured by Andrianova et al[12] using kilohertz-frequency AC, when compared with those of Kots and Xvilon[11] using low-frequency PC, in our opinion, lend support to the choice of a burst-modulated AC stimulus regimen, but the evidence is not conclusive. Direct comparisons of muscle force-generating regimens that use different "on/off" times and treatment schedules (duration and number of times per day per week) are needed, as are further direct comparisons of force production using low-frequency PC and modulated kilohertz-frequency AC.

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