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Toward the Optimal Waveform for Electrical Stimulation

Scott Douglas Bennie

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LOMA LINDA UNIVERSITY

School of Allied Health Professions

TOWARD THE OPTIMAL WAVEFORM FOR ELECTRICAL STIMULATION

By

Scott Douglas Bennie

A Publishable Paper in Lieu of a Thesis in
Partial Fulfillment of the Requirements for the Degree
Doctor of Physical Therapy Science

June 2001

Each person whose signature appears below certifies that this publishable paper in his/her opinion is adequate, in scope and quality, as a publishable paper in lieu of a thesis for the degree Doctor of Physical Therapy Science.

Chairperson

Jerrold S. Petrofsky, Professor of Physical Therapy

Grenith J. Zimmerman

Grenith J. Zimmerman, Professor of Biostatistics

Raymond G. Hall, Jr., Professor of Physiology

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Abstract

TOWARD THE OPTIMAL WAVEFORM FOR ELECTRICAL STIMULATION

By

Scott Douglas Bennie

Electrical stimulation (ES) is used to strengthen muscle, improve abnormal tone, and improve the healing rate of pressure sores. Four male and three female research subjects received four minute bouts of electrically stimulated isometric contractions equal to 10% of the maximal voluntary contraction (MVC) of their right quadriceps muscle to study subjective comfort and physiological responses to different waveforms, including Russian, interferential, sine, and square. Frequency remained constant at 30pps. The pulse width for the Russian waveform was 200μs, while the sine, square, and interferential waveforms used a 100μs pulse width. The amplitude of stimulation was adjusted to maintain the contraction elicited by ES at 10% of MVC. A visual analog scale (VAS) and verbal response scale (VRS) were used to monitor subjective comfort levels. Measures of physiological response including skin temperature change (local and systemic), surface blood flow, systolic and diastolic blood pressure (SBP and DBP), heart rate (HR), ventilation (V_E), oxygen consumption (VO_2), carbon dioxide production (VCO_2), respiratory quotient (RQ), and galvanic skin resistance (GSR) were recorded for a one- to two-minute baseline, during each four-minute contraction, and for a five minute recovery period. A contraction equal to 10% of the MVC was unable to be stimulated using the interferential waveform. The stimulated contractions utilizing the sine waveform required significantly less mean stimulation current to maintain the desired force of contraction with lower VAS and VRS scores. V_E, VO_2, and VCO_2 increased during the electrically stimulated isometric contractions as a response to the isometric exercise and not as a sympathetic response to noxious stimuli. Galvanic skin resistance, which is used to measure the sympathetic nervous system's response to painful stimuli, showed a consistently greater increase during Russian waveform stimulations. The sine waveform allows the desired muscle tension to be stimulated with the least tissue trauma while providing the most subjective comfort.

Keywords: Electrical stimulation (ES), Isometric exercise, Waveform, Comfort, Physiological response

Electrical stimulation (ES) is used to strengthen healthy muscle (McMiken et al. 1983; Selkowitz 1985; Godfrey et al. 1979; Laughman et al. 1983), reduce spasticity (Scheker et al. 1999), decrease pain (Loeser et al. 1975; Moore and Shurman 1997; Repperger et al. 1997), and improve healing rates of pressure sores (Petrofsky 2000; Stefanovska 1993). Electrical stimulation also reduces muscular atrophy (Eriksson and Häggmark 1979). Few studies use the same stimulation parameters or waveforms, making comparison of studies difficult at best. Moreover, each manufacturer of electrical stimulation units claims that their parameters, or combination of parameters, are the most effective in achieving the desired treatment goals. When the desired treatment goal is muscle strengthening, there are three major considerations when evaluating which stimulation waveform is best for both clinical medicine and research: the mean stimulation current required to achieve muscle contraction, the subjective comfort of the stimulation, and the physiological responses to the electrical stimulation, which are the objective measures of comfort and possible tissue injury. Attempts to increase the amplitude or intensity of ES during human research and clinical applications are often limited by subjective complaints of discomfort.

In an effort to minimize discomfort, many previous studies have attempted to determine which waveform or waveform parameters (e.g. frequency and pulse width) or combination of parameters caused the least patient discomfort. In one study, there was no simple answer. Individuals had their own preference for a given sinusoidal, triangular, or square waveform (Delitto and Rose 1986). In another study, a symmetric biphasic square waveform was generally preferred for the large quadriceps muscle group, whereas an asymmetric biphasic square waveform was preferred for the smaller forearm musculature, when compared to a monophasic paired spike and three medium frequency waveforms (Baker et al. 1988). Russian and interferential waveforms are frequently used medium-frequency waveforms. The Russian waveform utilizes a sinusoidal waveform at a 2500 Hz carrier frequency, whereas the interferential combines two higher-frequency waveforms (e.g. 4000 and 4100 Hz) in a crossed pattern, so that the net frequency resulting from the cancellation/reinforcement phenomena at or near the crossing points equals 100 Hz (Kahn 1991). Individual preference also seems to occur when burst and carrier frequency modes are compared for comfort (Rooney et al. 1992).

Changes in frequency seem to have an effect on torque production. By increasing the frequency, greater comfort is achieved with a resultant decrease in torque production. Some studies for square wave stimulation suggest that a frequency of 50 Hz creates a balance between comfort and torque production (Ward and Robertson 1998). Generally, a muscle contraction will grow stronger as the intensity of stimulation increases due to the recruitment of more motor units with activation of more muscle fibers, which produces greater strength (Selkowitz 1985). But intensity is often limited in both research and clinical settings by subjective complaints of pain.

The visual analog scale (VAS) and the verbal rating scale (VRS) have been used in many previous studies to rate subjective complaints of discomfort. Although the VAS (Price et al 1983) and the VRS (Downie et al. 1978) are valid, they make the comfort variable used in these studies purely subjective. Clinically, it is difficult to ascertain whether a patient's subjective report of 8/10 pain on the VRS one week is comparable to a similar score at a later time. Therefore, objective, valid, and reliable measures of pain have been sought by examining physiological responses.

In an effort to objectively quantify the optimum waveform and stimulation parameters, physiological responses have also been studied. The magnitude of changes in blood flow during ES application has varied among studies. Significant increases in skin temperature have been noted both ipsilaterally and contralaterally following sub-motor threshold transcutaneous electrical nerve stimulation (TENS) of 20 to 45 minutes in duration (Abram et al. 1980) and following 60 minutes of unilateral, low frequency neuromuscular electrical stimulation (NMES) at an intensity sufficient to produce visible contractions of the musculature in subjects with peripheral vascular disease (Loubser et al. 1988). Dramatic increases in current flow result in a rise in temperature under the electrode and a decrease in ph at the skin. This drop in ph results in tissue damage, leading to burns involving cutaneous and even subcutaneous tissues (DiVincenti et al. 1969). These electrically induced burns have been studied both in animal experimental studies (Sances et al. 1981) and in human case studies following functional electric stimulation use (Balmaseda et al. 1987).

A contralateral increase in limb blood flow has been seen briefly following a static voluntary contraction of the opposite quadriceps muscle (Gaffney at al. 1990). This finding differs from another study in which no significant limb blood flow changes were noted with intensities either above or below motor threshold (Indergand and Morgan 1994). Neuromuscular ES can be used to increase microvascular perfusion in the stimulated skeletal muscle (Clemente et al. 1991), but the intensity should be increased to a level to stimulate a muscle contraction (Clemente and Barron 1993). Positron emission tomography has shown that the greatest increases in blood flow occur in the muscles closest to the electrode, with an exponential decrease in flow as distance from the electrode increases (Vanderthommen et al. 2000).

During non-fatiguing voluntary isometric exercise, a linear rise in systolic and diastolic blood pressures occurs over time (Davies and Starkie 1985). It is suggested that the cause of the rise in blood pressures in response to isometric exercise is the release of a metabolite, possibly potassium, from the isometrically contracting muscles that stimulate type III and IV sensory fibers (Lind et al. 1964; Hnik et al. 1969), which in turn cause a splanchnic sympathetic vasoconstriction and a modest increase in cardiac output (Petrofsky 1982). Non-fatiguing isometric contractions result in a rise in blood pressures that is proportional to the tension exerted by the contracting muscles (Petrofsky 1982). If a voluntary isometric contraction is maintained at a non-fatiguing tension (<15% MVC), the blood pressure achieves a steady state following the initial rise (Lind and McNicol 1967). Similar increases in systolic and diastolic blood pressures occur during involuntary, or electrically stimulated, isometric contractions (Davies and Starkie 1985).

The heart rate response to voluntary isometric contractions at non-fatiguing tensions are similar to BP changes in that there is only a small increase in heart rate that attains a steady state after approximately two minutes (Lind and McNicol 1967). Voluntary isometric contractions cause a greater increase in heart rate than involuntary, or electrically stimulated isometrics (Davies and Starkie 1985; Goldberg et al. 1982). Many studies suggest that the heart rate response is centrally mediated, caused by signals from the central nervous system resulting in a withdrawal of cardiac vagal tone (Coote et al. 1971; Freyschuss 1970; McCloskey and Mitchell 1972), unlike the aforementioned blood pressure response, which is more peripherally mediated (Petrofsky 1982).

Ventilation (V_E) has been shown to increase during voluntary isometric exercise (Mitchell et al. 1977) due to a rise in tidal volume and a reduction in expiratory duration (Paulev et al. 1991). In electrically induced rhythmic-static single leg exercise, a significant initial rise in V_E and oxygen uptake (VO_2) was noted, followed by an achievement of a steady state (Spengler et al. 1994). There was a greater correlation between these two variables, V_E and VO_2, during electrically stimulated contractions than during voluntary isometric exercise (Spengler et al. 1994).

This study provided a comprehensive examination of subjective, objective, and physiological responses to electrically stimulated isometric contractions of the quadriceps femoris muscle utilizing four different waveforms. This study related tension developed in muscle during electrical stimulation to subjective discomfort and physiological responses in an attempt to assess and possibly correlate subjective and objective responses. The VAS and VRS provided subjective ratings of comfort. Galvanic skin resistance monitored sympathetic activity via perspiration to determine an objective comfort measure (Danilov et al. 1994). Physiological responses including skin temperature, forehead surface pulsatile blood flow, systolic and diastolic blood pressure, heart rate, ventilation (V_E), oxygen consumption (VO_2), carbon dioxide production (VCO_2), and respiratory quotient (RQ) were measured.

Methods

Subjects

Seven subjects, volunteers recruited from the university and community, participated in the study. The subjects, four males and three females, were between 20 and 60 years of age and had no known dermatological, musculoskeletal, or neuromuscular disorders or pathologies. None had any history of major knee injury nor had participated in any vigorous exercise for a minimum of 12 hours prior to each day of the study. Any subject currently pregnant or previously diagnosed with hypertension was excluded from the study.

The purpose of this research, as well as the protocol and procedures involved, were explained in detail to each subject by a researcher. An informed consent form, approved by the Institutional Review Board, was read and signed by each subject in the presence of the investigator and a witness. Anthropometrical measures were then recorded.

Instrumentation

Electrical stimulation. The Challenge 8000A muscle stimulator (MPTS, Inc., Irvine, CA) delivered the electrical stimulation for the square and sine waveform tests during both Series 1 and Series 2. A Chattanooga Forte 400 Combo stimulator (Chattanooga, TN) provided the stimulation for the Russian and interferential tests. Electrodes used to deliver the electrical stimulation were two by four inch rectangular-shaped carbon rubberized electrodes (Unipatch, part #658). Electrical impedance was measured at 200 cycles per second on each quadriceps muscle, with the points with the lowest impedance being determined to be the motor points. The skin was cleansed with alcohol and electrodes were placed directly over the motor points with exact placement being recorded for precise and reliable placement for the second day of the study. A bipolar electrode placement was used during the square, sine, and Russian waveform stimulations. The electrodes were placed directly on the skin over the proximo-lateral and disto-medial quadriceps muscle. A quadripolar electrode arrangement was used during the interferential stimulation with the additional electrodes placed over the proximo-medial and disto-lateral quadriceps. Current was delivered with a ten-ohm resister placed in series with the electrode. Voltage drop across the resister was measured using a Tektronics digital oscilloscope to determine the current being applied through the skin. During each stimulated contraction, the waveform was captured on the oscilloscope and printed out for later analysis.

Isometric quadriceps strength. Subjects were seated in a specially designed chair that utilized motor drives to place the hips and knees in 90 degrees of flexion (Figure 1). Each distal femur rested in an individually padded U-shaped support that maintained the hips in a neutral position in the coronal plane while allowing the knees to remain dependent at 90 degrees of flexion. Each lower extremity was independently fixed distally via sheepskin-padded leather ankle cuffs 2.0 cm proximal to the malleoli. These ankle cuffs were attached to a stainless steel bar. The forces produced by the isometric quadriceps contractions were measured using an isometric strain gauge device consisting of four strain gauges arranged in a Wheatstone bridge that was attached to this stainless steel bar. One hundred kilograms of force was required to bend the bar $5/10^6$ of an inch.

Output was amplified using a Biopac strain gauge amplifier with a gain of 5000 and a common mode rejection ratio of 120 db. The electric signal was digitized in an A-D converter with a 16-bit resolution at 1000 samples per second.

Figure 1. Specially designed chair that utilized motor drives to maintain lower extremities in desired position and measure isometric quadriceps force throughout the duration of the study.

Surface pulsatile blood flow. A Hertzman photoelectric plethysmograph (Hertzman and Flath 1966)(Mallencrodt Corp., St. Louis, MO) was employed to determine changes in pulsatile surface blood flow on each subject's forehead. The area under each pulse was measured to determine the pulsatile blood flow.

Skin temperature. Skin temperature was measured under the proximal vastus lateralis electrode using a thermoster probe placed directly under the active electrode. Temperatures were also measured on the forehead and at the medial belly of the left quadriceps muscle. These thermoster probes were suspended in Plexiglass cylinders 4-cm in diameter and 1-cm in height. Each cylinder had four Plexiglass circular feet 1.2-cm in diameter and 0.5-cm in height secured to it for stability, to allow for good airflow over the skin, and to reduce the possibility of circulatory occlusion. The thermoster probe was centered in the cylinder and secured to the Plexiglass feet by wire so that the probe would be in constant contact with the skin surface. The cylinders were secured with 1.0-centimeter-wide Velcro straps. Changes in electrical resistance from the thermoster were transduced to an electrical output via the Biopac electrical thermoster amplifier that had a gain of 1000. The electric signal was digitized in an A-D converter with a 16-bit resolution at 200 samples per second. Room temperature was maintained at 23°C (± 1°C).

Respiratory parameters. Ventilation (V_E STPD), oxygen consumption (VO_2), carbon dioxide production (VCO_2), and respiratory quotient (RQ) were measured during Series 2 stimulations using the Aerosport VO 2000 portable metabolic cart. The metabolic cart uses a fuel cell to measure VO_2, infrared spectroscopy to measure VCO_2, and a differential pressure transducer to measure ventilation. Barometric pressure and gas volumes were calibrated at the beginning of each morning and afternoon of data collection. A mouthpiece was inserted into each subject's mouth with a padded clamp placed on the nose, as Figure 2 demonstrates, to force the expired gases into the metabolic cart for analysis. Data collected from the Aerosport VO2000 was brought into the computer via a serial port at 19,600-baud and managed with the Aerograph computer program.

Figure 2. Subject utilizing the mouthpiece and nose clip of the Aerosport VO2000 portable metabolic cart to measure V_E, VO_2, VCO_2, and RQ during the 4-minute-long contractions.

Blood pressure. Blood pressure was measured by auscultation of the left upper arm. A stethoscope was placed on the left antecubital fossa; the calibrated sphygmomanometer was inflated to 180 mmHg, and then released at 3 mmHg per second as per American Heart Association standards (ACSM 1995). Systolic blood pressure was determined as the initial appearance of sound by auscultation. Diastolic blood pressure was determined as the first change in sound from sharp to muffled. Blood pressures were taken every 30 to 40 seconds during the 60 to 120-second baseline period, throughout the stimulation, and during the five-minute recovery period. The same researcher made all of the blood pressure measurements. The blood pressures were then input manually into the Aerosport computer program for later analysis.

Heart rate. Pulsatile blood flow measured by a Hertzman photoelectric plethysmograph (Mallencrodt Corp., St. Louis, MO) on each subject's forehead was used to determine the heart rate. The output was amplified using a Biopac strain gauge amplifier with a gain of 5000. The electric signal was digitized in an A-D converter with a 16-bit resolution at 200 samples per second. The distance between peaks of the pulsatile blood flow wave was measured and heart rate, in beats per minute (bpm), was calculated.

Galvanic skin resistance. Two small galvanic skin resistance electrodes (Biopac) were secured to the index and middle fingers of the right hand with 1.0-centimeter-wide Velcro strips. A neutral electrode gel was placed between the electrode and the skin. These electrodes measured the change in resistance through the skin. Output was amplified using a Biopac strain gauge amplifier with a gain of 5000. The electric signal was digitized in an A-D converter with a 16-bit resolution at 200 samples per second.

Subject comfort. Two measures of subjective comfort were used during each contraction. The visual analog scale (VAS) consisted of a 7.6-centimeter line; the left extreme labeled “Severe discomfort,” and the right extreme “No discomfort.” Subjects were asked to rate their discomfort by making a perpendicular line on the scale that corresponded to their level of discomfort. The researcher calculated the proportional score for each test on the typical 10-centimeter visual analog scale and recorded the score on the data collection sheet. The verbal rating scale (VRS) was used after each subject had completed the visual analog scale. The subjects were instructed to rate their pain on a 0 to 10 scale, 0 being no pain, 10 being severe pain. Previous VAS and VRS scores were hidden from each subject to prevent bias. If a subject reported severe discomfort or pain on the VAS or the VRS during the stimulation, that trial was stopped immediately. The verbal rating scale results were recorded on the data collection sheet.

Data Management

Data was managed using the AcqKnowledge 4.0 and Aerosport VO2000 computer programs that displayed on a 20-inch monitor and was saved on disc for later analysis. Subjective comfort scores were recorded manually on the data collection form.

Procedures

Anthropometric measures including gender, age, height, and weight were obtained and recorded. Subjects were seated in the specially designed chair and the motor drives were used to position the subjects properly to maintain the 90/90 position. Ankle cuffs were secured and the lever arm, the distance from the medial knee joint space to the medial malleolus on the right lower extremity, was measured and recorded.

Subjects were instructed in the usage of the visual analog scale (VAS) as well as the verbal rating scale (VRS). Three maximal voluntary contractions (MVC), one minute apart, were obtained for right knee extension. The MVC that elicited the greatest isometric strength was recorded and used to calculate the contraction strength to be elicited during the electrically stimulated contractions, which was 10% of the MVC. Each subject received an introductory standardized 10-second stimulation utilizing a square waveform, 30 pps frequency, and 100-microsecond pulse width with an amplitude facilitating a contraction equal to 10% of their MVC.

The study consisted of four 4-minute contractions, each utilizing one of the aforementioned waveforms applied in a random order. Frequency was maintained at 30 pps for all waveforms. Pulse width varied as follows: 100-μs for interferential, sine, and square waveforms and 200-μs for the Russian waveform. Amplitude was manipulated to maintain a contraction equal to 10% of the subject's MVC. Only two of these four-minute contractions were stimulated per day with a minimum of 10 minutes rest between them. The two days of data collection were at least 48 hours apart to minimize the possibility of fatigue.

Mean stimulation current across the skin, both subjective pain measures, skin temperature, surface pulsatile blood flow, systolic and diastolic blood pressures, heart rate, respiratory parameters, and galvanic skin resistance measures were recorded for a minimum of one-minute baseline, four-minutes during the contraction, and for a five-minute recovery period following the contractions. Subjects remained seated in the chair between stimulations.

Data analysis

Data was retrieved from the data collection form, AcqKnowledge 4.0 computer software, and the Aerograph computer program for analysis. Means and standard deviations were calculated for each of the anthropometric measures. Means, standard deviations, standard error, and repeated measures ANOVA with pairwise comparisons were calculated for the mean stimulation current, subjective discomfort scales, and the physiological responses to monitor within-waveform changes over time and between waveforms at specific points in time. The level of significance used in all statistical tests was $\alpha=0.05$. In the results section the symbol "±" is always followed by the standard error. Standard deviations, when used, will be noted as "SD."

Results

The mean age of the subjects was 33.1 years (SD=16.4). The mean height for the males was 174.6 cm (SD=6.67), while the females had a mean height of 162.6 cm (SD=7.65). Mean weight for the males was 79.3 kg (SD=14.6) and for the females, 58.3 kg (SD=1.33).

The maximal voluntary contraction (MVC) for right knee extension was recorded at the beginning of each day of data collection (Table 2). The mean difference in MVC between Day 1 and Day 2 was 4.3 kg (SD=4.3). Subject six completed only Day 1 of the study.

Table 1. Maximal voluntary contraction (MVC) strength for each subject.

Subject #	Right knee extension strength (kg)		
	Day 1	Day 2	Difference (Day1-Day 2)
1	41.8	35.9	5.9
2	38.2	36.4	1.8
3	38.2	38.2	0
4	36.8	27.7	9.1
5	29.5	20.5	9.5
6	17.7		
7	35.0	35.0	0
Mean			4.4
SD			4.3

Three subjects completed the 4-minute electrically stimulated isometric contractions with all of the waveforms. Subject number seven did not complete the contraction utilizing the Russian waveform due to a systolic blood pressure exceeding 180 mmHg. All other stimulated contractions shorter than the four minutes (240 seconds) were due to complaints of severe discomfort or pain on the visual analog scale (VAS) or the verbal rating scale (VRS) (Figure 3).

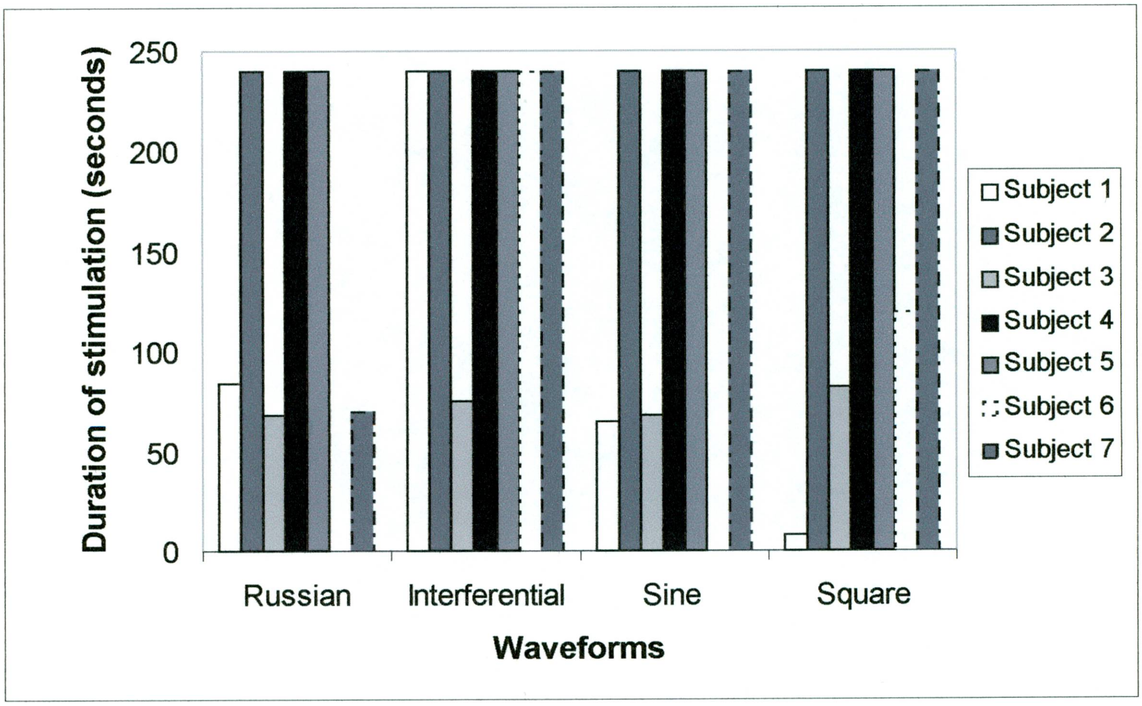

Figure 3. Duration of stimulation (seconds) tolerated by each subject per waveform. A maximum of 240 seconds, or 4 minutes was possible.

Mean stimulation current

There was a significant rise in mean stimulation current from "immediate time," the time immediately following the attainment of the desired contraction strength, to one minute into the stimulation using the sine waveform (0.25 mA ± 0.03, 0.30 mA ± 0.03 respectively; $p=0.003$). No significant changes in mean stimulation current were found within the Russian, interferential, or square waveforms over the 4-minute contraction elicited by electrical stimulation. The mean stimulation current required to maintain a 4-minute contraction equal to 10% of the MVC was consistently lower with the sine waveform than with the square waveform, as shown in Figure 4. The sine waveform stimulations required significantly less mean stimulation current to achieve the desired contraction strength at the "immediate time" than the square wave stimulations (0.21 mA ± 0.02, 0.59 mA ± 0.04 respectively; $p=0.01$). Halfway through the stimulated muscle contraction (2-minute mark), the stimulations using the sine waveform required a mean stimulation current of only 0.33 mA (± 0.05), which is significantly less ($p=0.004$) than was required to maintain the desired contraction when the square waveform (1.02 mA ± 0.04) was used. Even though a contraction equal to 10% of the MVC could not be reached, the stimulations using the interferential waveform required significantly greater mean stimulation current than either the sine or square waveforms ($p<0.001$, $p<0.001$ respectively). The mean stimulation current during stimulations using the Russian waveform was significantly higher than either the sine ($p<0.001$) or square waveforms ($p<0.001$) at each measured time during the 4-minute isometric contractions.

In each of the following figures, the label "SO" indicates the time when the contraction elicited by electrical stimulation attained an isometric contraction of the quadriceps at 10% of the MVC.

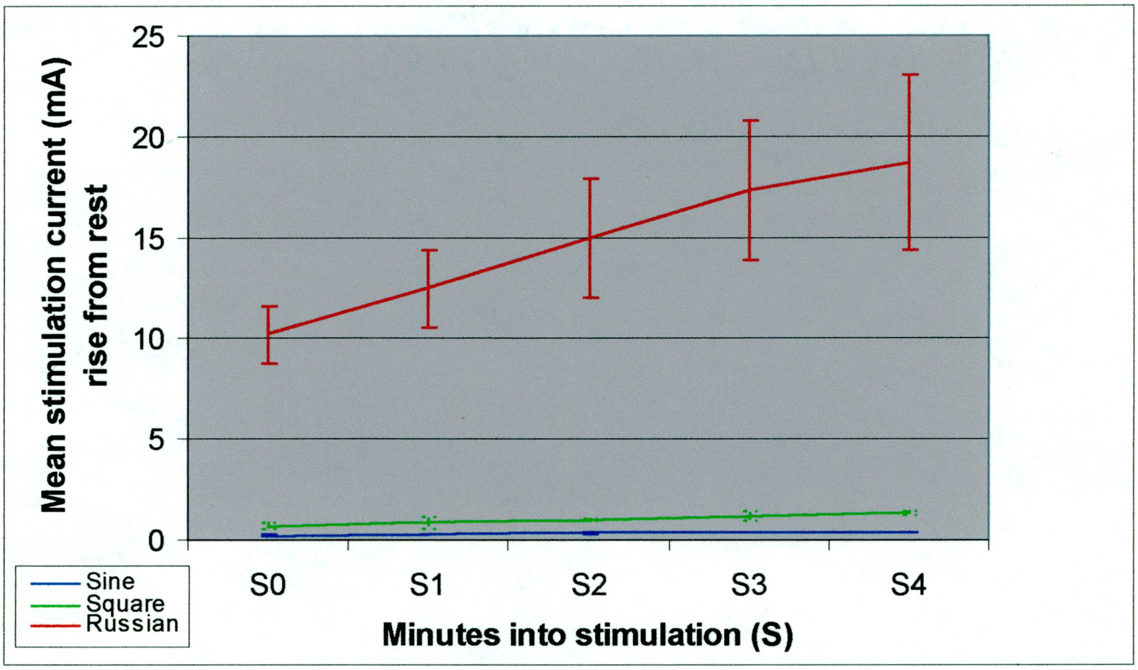

Figure 4. Mean stimulation current (mA) rise across the skin during the 4-minute long stimulated contraction. Error bars indicate standard error.

Visual analog scale

The visual analog scale (VAS) demonstrated no significant differences (p>0.05) in the subjective discomfort experienced during the 4-minute long contractions among the Russian, sine, and square waveforms, nor were there any significant changes (p>0.05) in mean VAS scores within any of the waveforms over the duration of the 4-minute contractions. Of note in Figure 5 is the decrease in mean VAS scores during the electrically stimulated contractions that made use of the sine waveform, although the difference was not significant (p>0.05) due to the increase in variability of the scores.

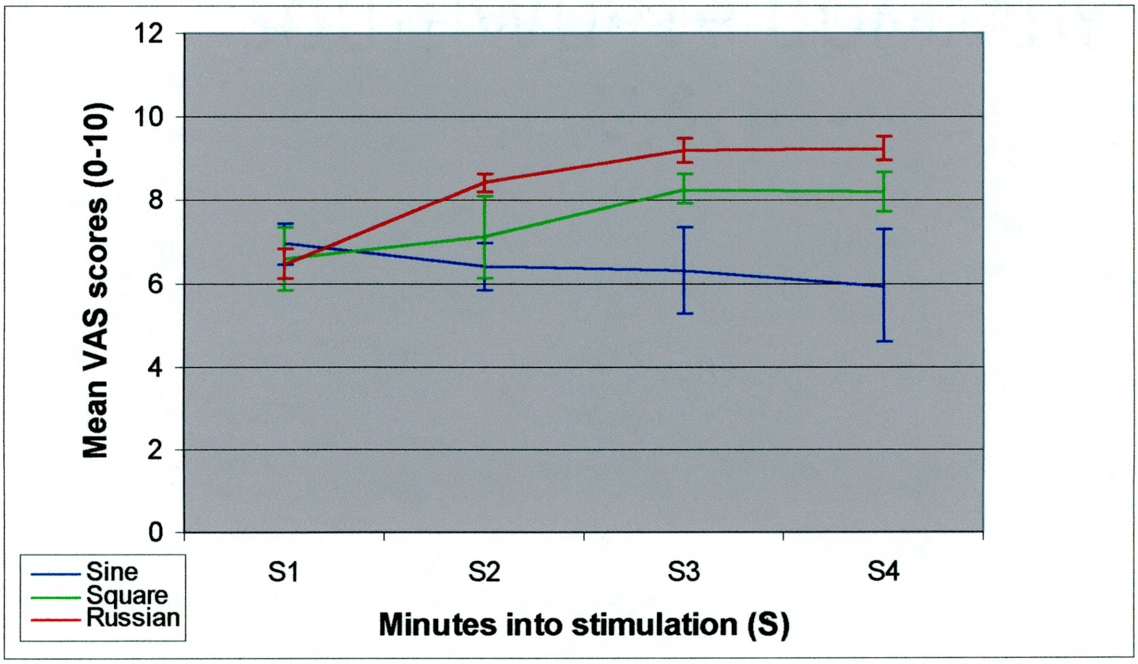

Figure 5. Mean visual analog scale (VAS) scores during the 4-minute long stimulated contraction. Error bars indicate standard error.

Verbal rating scale

The second subjective tool used to measure discomfort, the verbal rating scale (VRS), showed no significant differences (p>0.05) in subjective discomfort within or among the waveforms. The mean VRS scores throughout the 4-minute-long electrically stimulated contraction of the right quadriceps muscle, as shown in Figure 6, decreased from a mean of 7.0 (± 0.7) at the time immediately following attainment of the desired contraction force ("immediate time") to 6.3 (± 1.0) at the fourth minute of the contraction (p>0.05) when the sine waveform was employed.

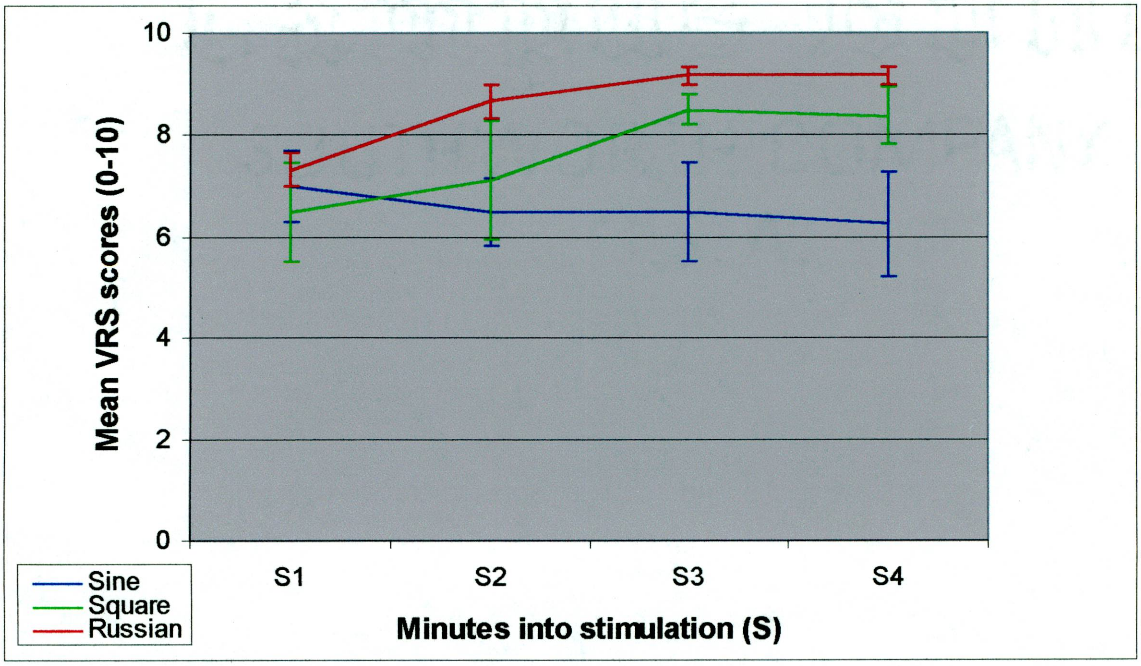

Figure 6. Mean verbal rating scale (VRS) scores during the 4-minute long stimulated contraction. Error bars indicate standard error.

Ventilation

The mean change in ventilation (V_E) was not significantly different ($p>0.05$) when within-waveform measures of ventilation were analyzed for the Russian, sine, and square waveforms throughout the 4-minute contraction and 5-minute recovery period. The mean increase in ventilation from baseline at the halfway point (2-minutes) of the contraction elicited by electrical stimulation was greater ($p=0.05$) when employing the sine (59.0% ± 14.7) waveform than while using the square (-4.25% ± 9.2) waveform, although not significantly greater than the Russian waveform (12.0% ± 40.0). The square waveform stimulations actually resulted in a decrease in ventilation during the same stimulation period, as shown in Figure 7.

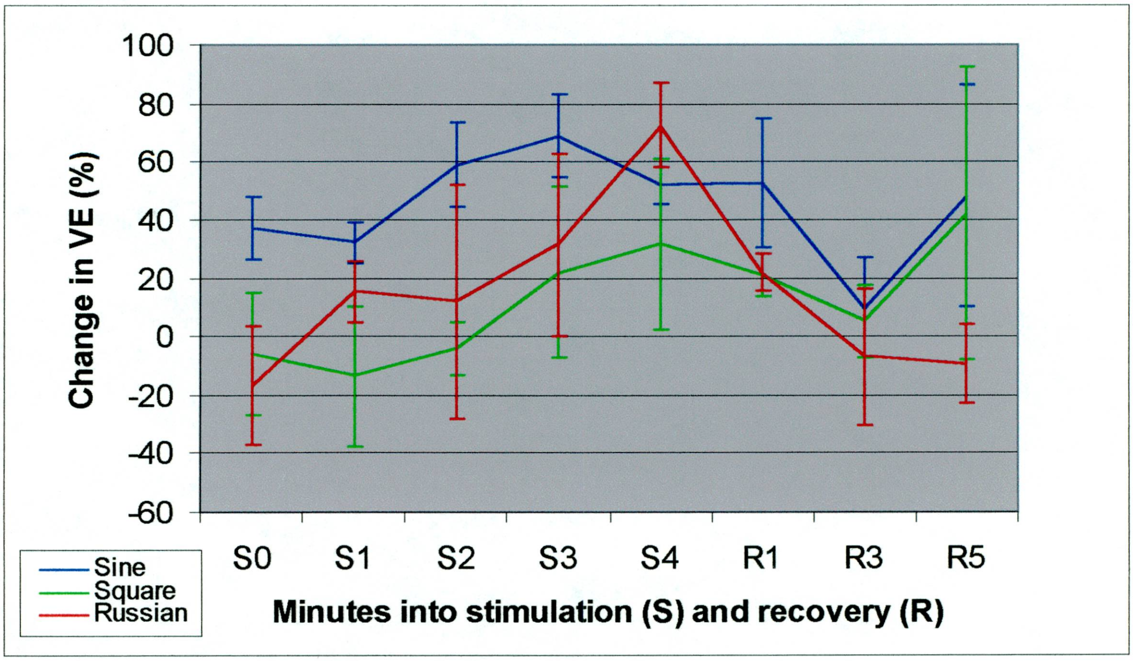

Figure 7. Mean change (%) from baseline in ventilation (V_E) during the 4-minute long stimulated contraction and 5-minute recovery period. Error bars indicate standard error.

Oxygen consumption

The mean change in oxygen consumption (VO_2) over the stimulation and recovery periods was not significant ($p>0.05$) when within-waveform measures were analyzed for the Russian, sine, or square waveforms. The mean VO_2 was consistently greater over the course of the 4-minute contractions that used the sine wave than those using either the Russian or square wave stimulation. An initial decrease in mean VO_2 to below baseline values, as seen in Figure 8, was noted during contractions using the square waveform, although the change was not significant ($p>0.05$).

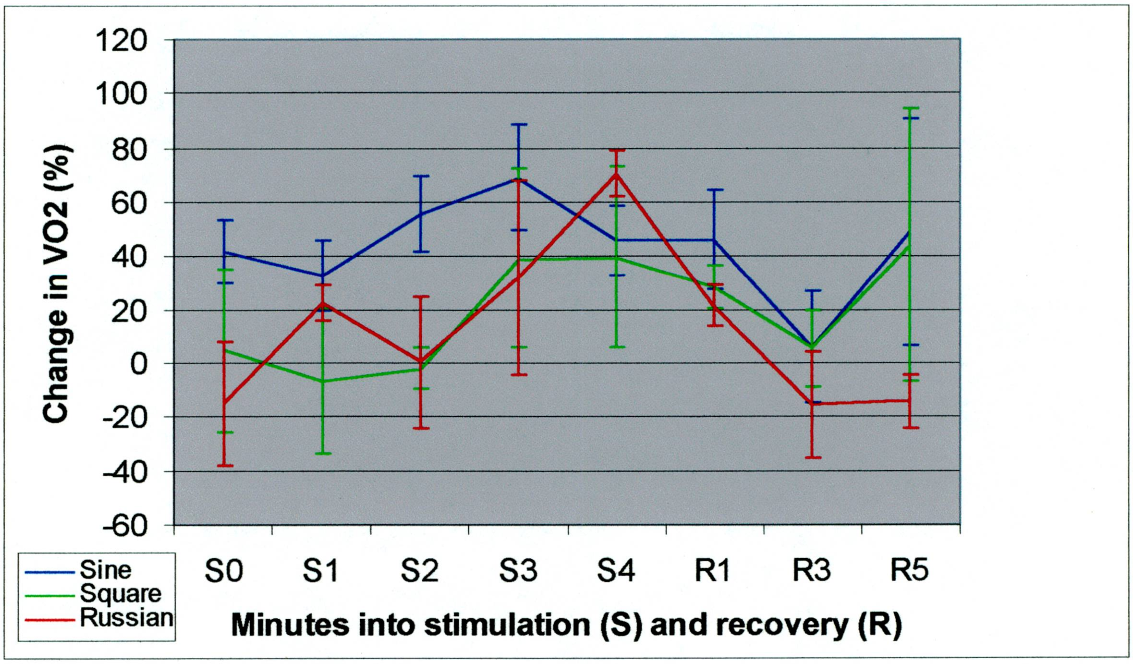

Figure 8. Mean change (%) from baseline in oxygen consumption (VO_2) during the 4-minute long stimulated contraction and 5-minute recovery period. Error bars indicate standard error.

Carbon dioxide production

There were no significant differences ($p>0.05$) in mean carbon dioxide production (VCO_2) when within-waveform measures were analyzed for the Russian, sine, and square waveforms over the 4-minute electrically stimulated isometric contraction and during the 5-minute recovery period. The production of carbon dioxide increased from rest during the contractions utilizing all three waveforms. Electrical stimulation using the sine waveform to elicit the isometric contraction produced greater production of carbon dioxide, although not significantly more ($p>0.05$), than did the Russian or square waveforms, as seen in Figure 9.

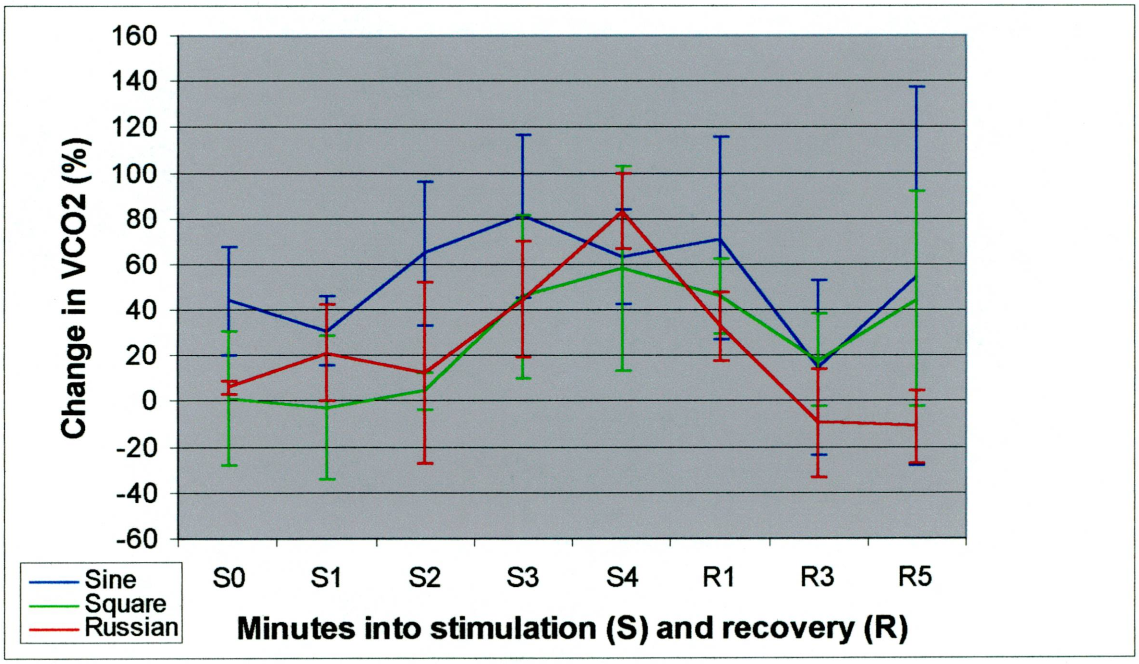

Figure 9. Mean change (%) from baseline in carbon dioxide production (VCO_2) during the 4-minute stimulated contraction and 5-minute recovery period. Error bars indicate standard error.

Respiratory quotient

The change from baseline of respiratory quotient (RQ), the ratio of carbon dioxide produced to oxygen consumed, over the 4-minute-long electrically stimulated contraction and the 5-minute recovery period did not significantly ($p>0.05$) differ among those contractions using the Russian, sine, or square waveforms. However, there was a large increase in variability during the recovery period following the utilization of the sine waveform. Figure 10 shows the similarity in rise of RQ following 4-minutes of the electrically stimulated contractions, with a mean increase of 12.5% (± 9.85) during the stimulations using the Russian waveform, 11.2% (± 3.4) during the sine waveform stimulations, and 11.4% (± 11.3) during the contractions elicited by electrical stimulation using the square waveform, although none of the increases were significant ($p>0.05$).

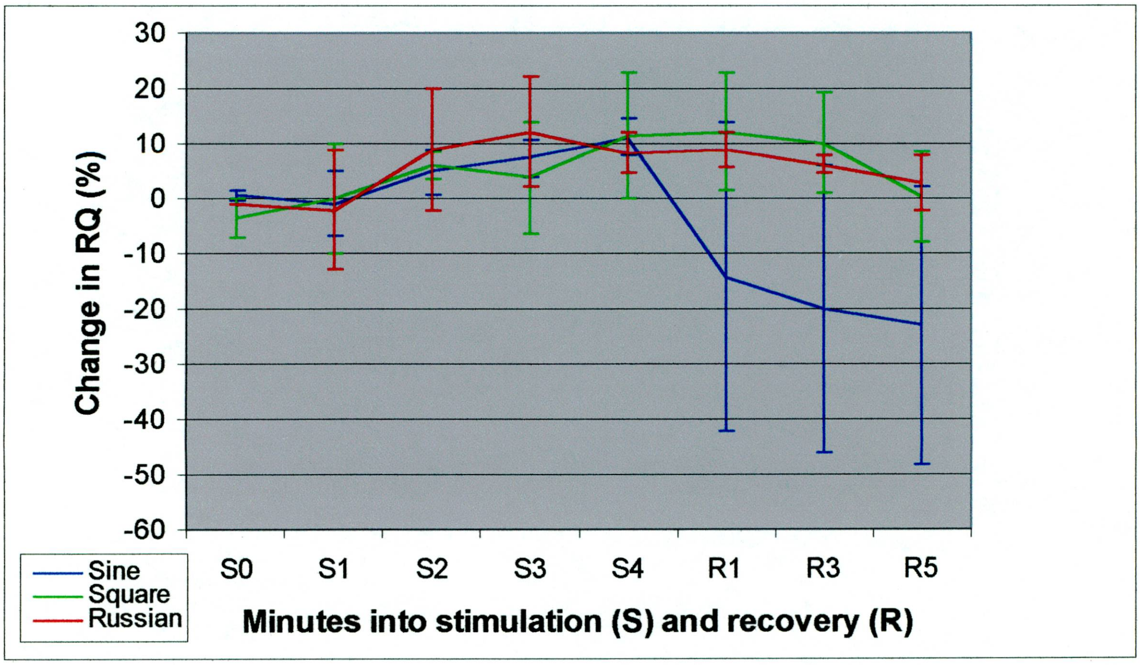

Figure 10. Mean change (%) from baseline in respiratory quotient (RQ) during the 4-minute stimulated contraction and 5-minute recovery period. Error bars indicate standard error.

Skin temperature under electrode

No significant differences in mean change in skin temperature under the stimulating electrode were found within waveform over time or among the Russian, sine, and square waveforms. However, a rise in skin temperature from rest, as measured under the proximal active stimulating electrode during the 4-minute-long contraction, was noted during the initial three minutes of the stimulation when utilizing each of the three waveforms. The three-minute rise was followed by a reduction of the skin temperature under the electrode over the last minute of the stimulation and throughout the recovery period, as Figure 11 shows, but this drop in skin temperature was not significant (p>0.05) for any of the three waveforms.

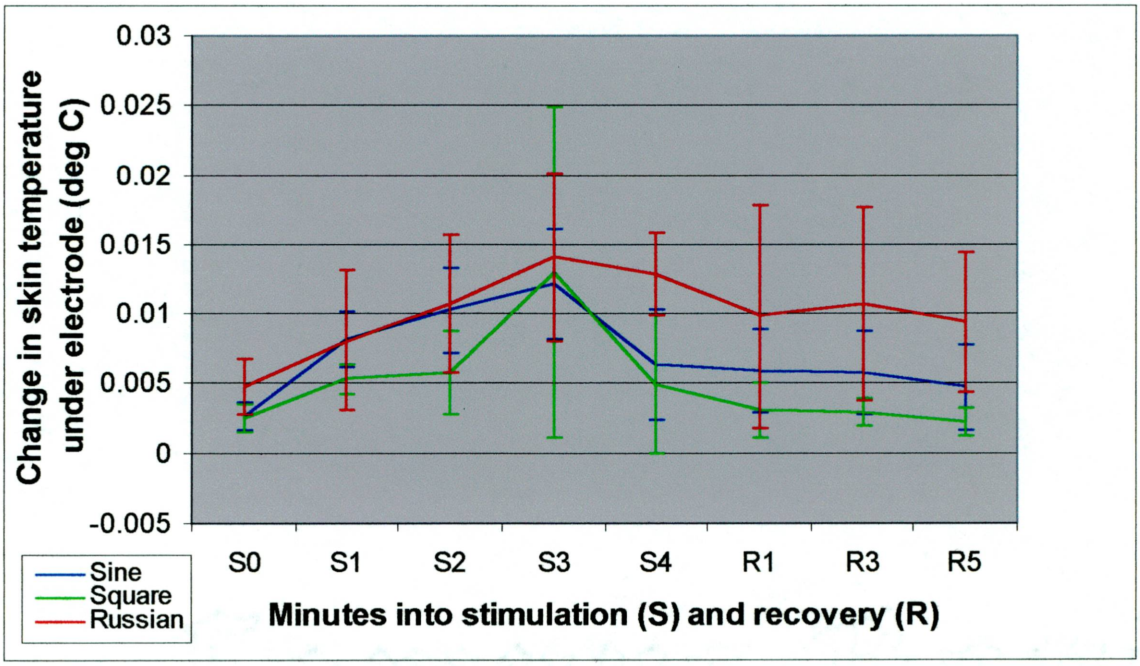

Figure 11. Mean change (°C) from baseline in skin temperature under the electrode during the 4-minute contraction and 5-minute recovery period. Error bars indicate standard error.

Skin temperature at the forehead

A mean increase from baseline in skin temperature at the forehead was found during the 4-minute electrically stimulated contraction. Although the stimulations using the square (0.47°C ± 0.18) waveform produced greater increases in skin temperature than those employing the Russian (0.38°C ± 0.15) or the sine (0.25°C ± 0.09) waveforms, the differences were not statistically significant (p>0.05). The stimulation utilizing the sine waveform produced a significant increase in skin temperature at the forehead between the "immediate time" and one-minute into the recovery period following the isometric contraction as is shown in Figure 12 (0.13°C ± 0.02, 0.49°C ± 0.04 respectively; p=0.05). No other significant changes in skin temperature at the forehead were found when within-waveform measures for the Russian, sine, or square waveform were analyzed.

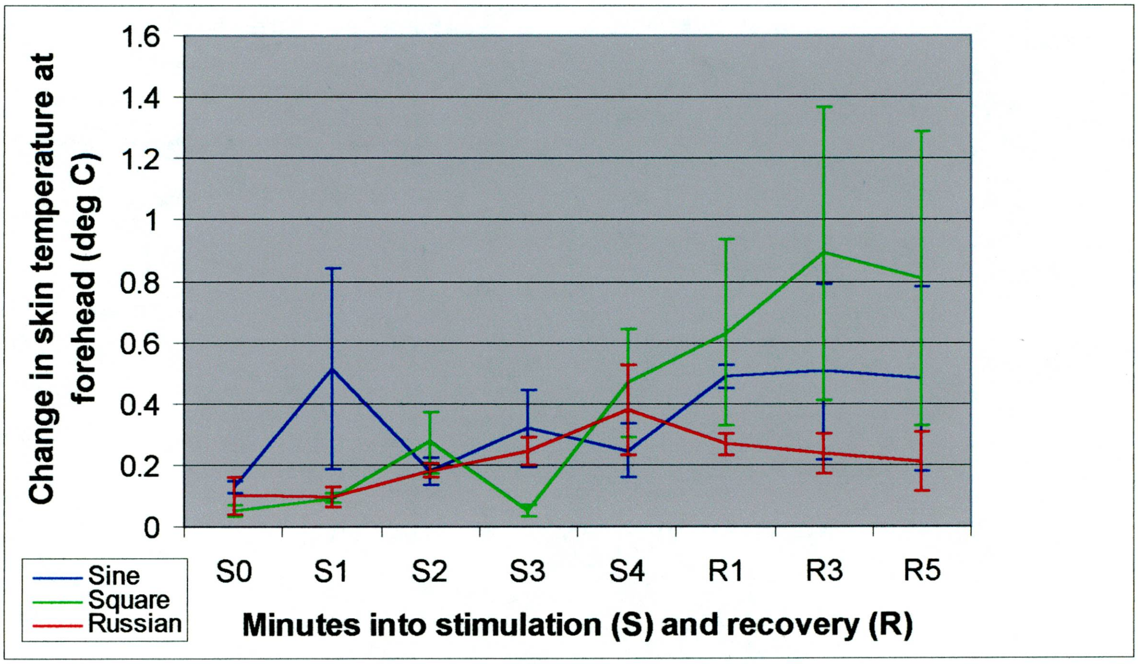

Figure 12. Mean change (°C) from baseline in skin temperature at the forehead during the 4-minute contraction and 5-minute recovery period. Error bars indicate standard error.

Skin temperature at the left quadriceps muscle

Mean skin temperature change measured on the left quadriceps muscle, the lower extremity that was not receiving the electrical stimulation, increased from rest over the duration of the contraction when utilizing either the Russian, sine, or square waveforms (Figure 13). A significant rise in skin temperature at the left quadriceps muscle was seen between the three-minute mark of the stimulated contraction and the one-minute mark of the recovery period when the square waveform was used during the electrical stimulation (0.02°C ± 0.02, 0.08°C ± 0.02 respectively; p=0.03). No other within or among waveform differences in left quadriceps skin temperature were significant (p>0.05).

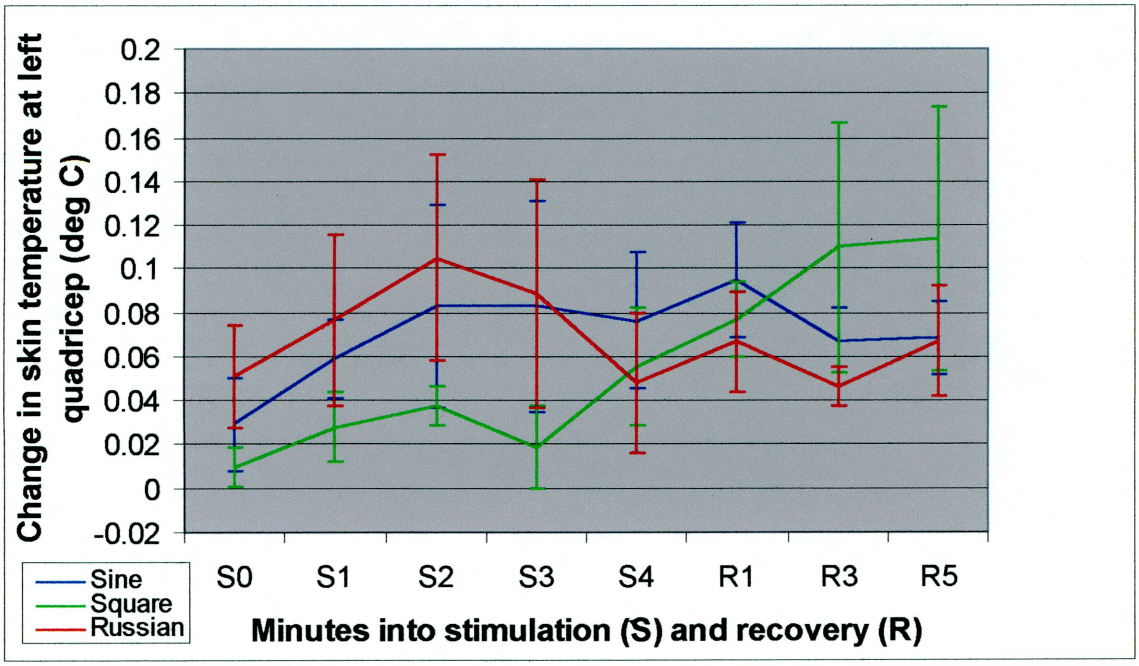

Figure 13. Mean change (°C) from baseline in skin temperature at the left quadriceps during the 4-minute contraction and 5-minute recovery periods. Error bars indicate standard error.

Surface blood flow

The stimulations employing the sine waveform increased surface blood flow by over 67% in the first minute of the electrically stimulated isometric contractions, while use of the square waveform produced a 125% increase in surface pulsatile blood flow by the fourth minute, although neither was significant (p>0.05) due to the large variability (Figure 14). The Russian waveform stimulations consistently produced the smallest increase in surface pulsatile blood flow during the 4-minute isometric contraction and returned to baseline by the end of the 5-minute recovery period. No significant differences among waveforms were noted (p>0.05).

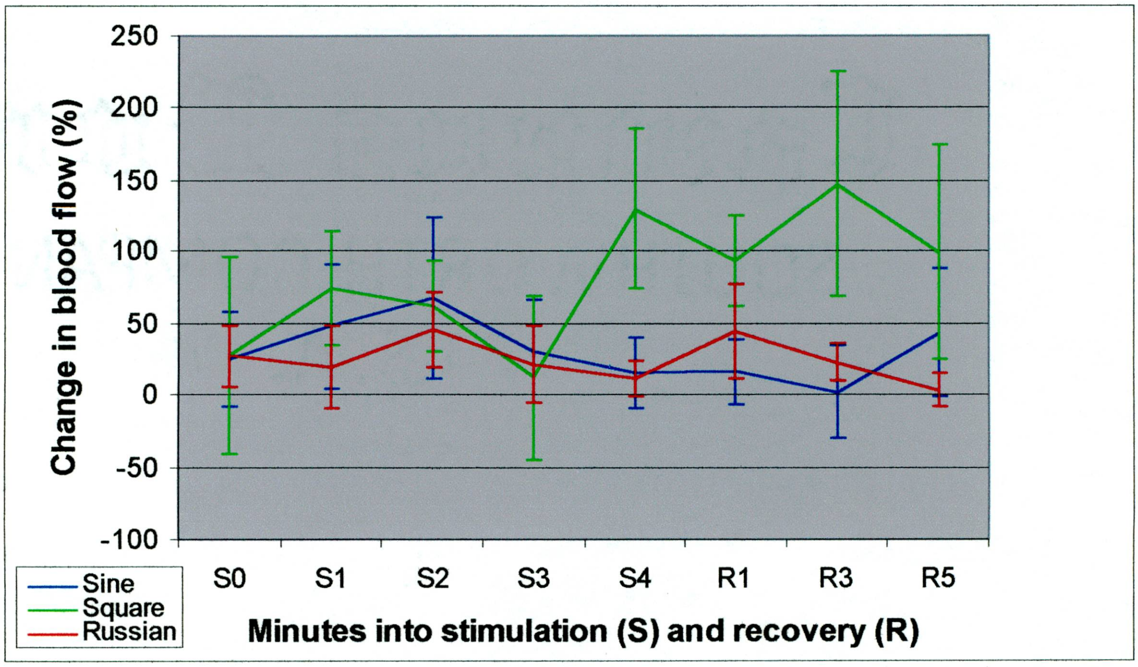

Figure 14. Mean change (%) from baseline in surface blood flow at the forehead during the 4-minute contraction and 5-minute recovery period. Error bars indicate standard error.

Systolic blood pressure

No significant differences in mean systolic blood pressure (SBP) were noted when within-waveform measures were analyzed for each of the waveforms. Mean rise from baseline in SBP was significantly higher following square wave stimulation as compared to the sine wave (11.69% ± 1.36, 7.33% ± 0.60 respectively; $p=0.04$)(Figure 15). The mean SBP following the contractions using the Russian waveform (11.7% ± 10.3) was not significantly different than following either the sine or square wave ($p>0.05$). However, at the "time immediate" and the 1-minute point of the stimulation, the contractions using the sine waveform resulted in a significantly greater ($p=0.04$, $p=0.02$, respectively) mean rise in SBP than those utilizing the square waveform.

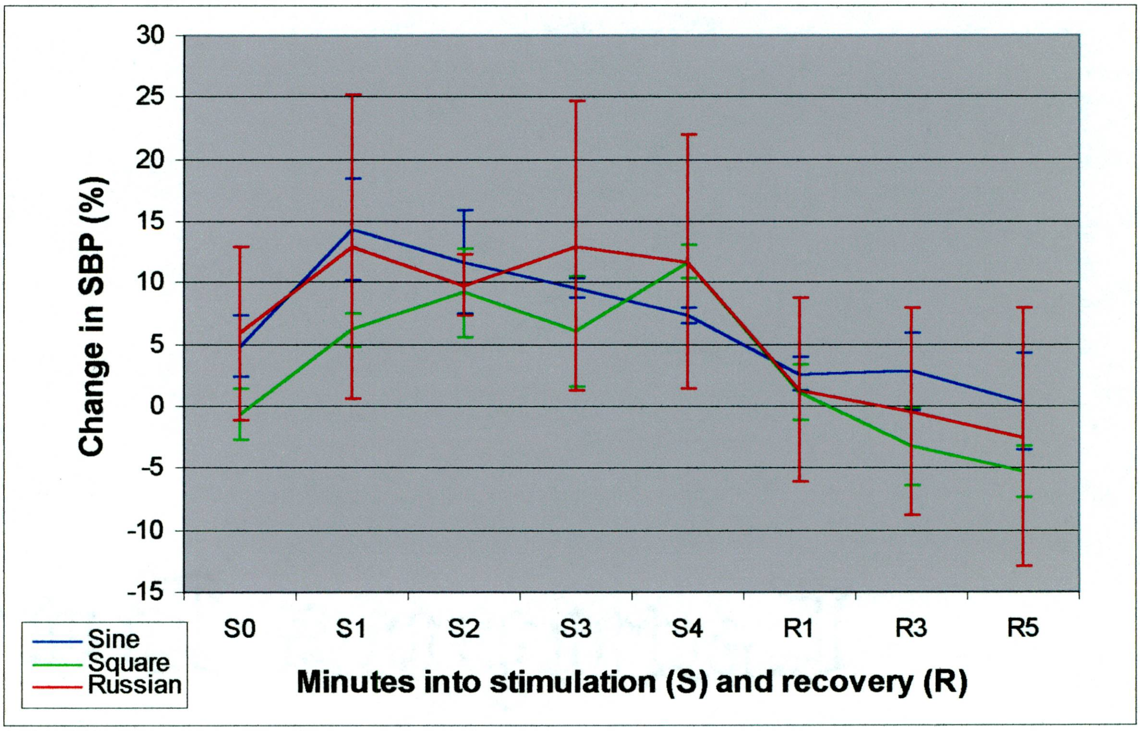

Figure 15. Mean change (%) from baseline in systolic blood pressure (SBP) during the 4-minute contraction and 5-minute recovery period. Error bars indicate standard error.

Diastolic blood pressure

The mean rise from baseline in diastolic blood pressure (DBP) during the contractions was not significantly different within or among the Russian, sine, and square waveforms (p>0.05), as Figure 16 shows.

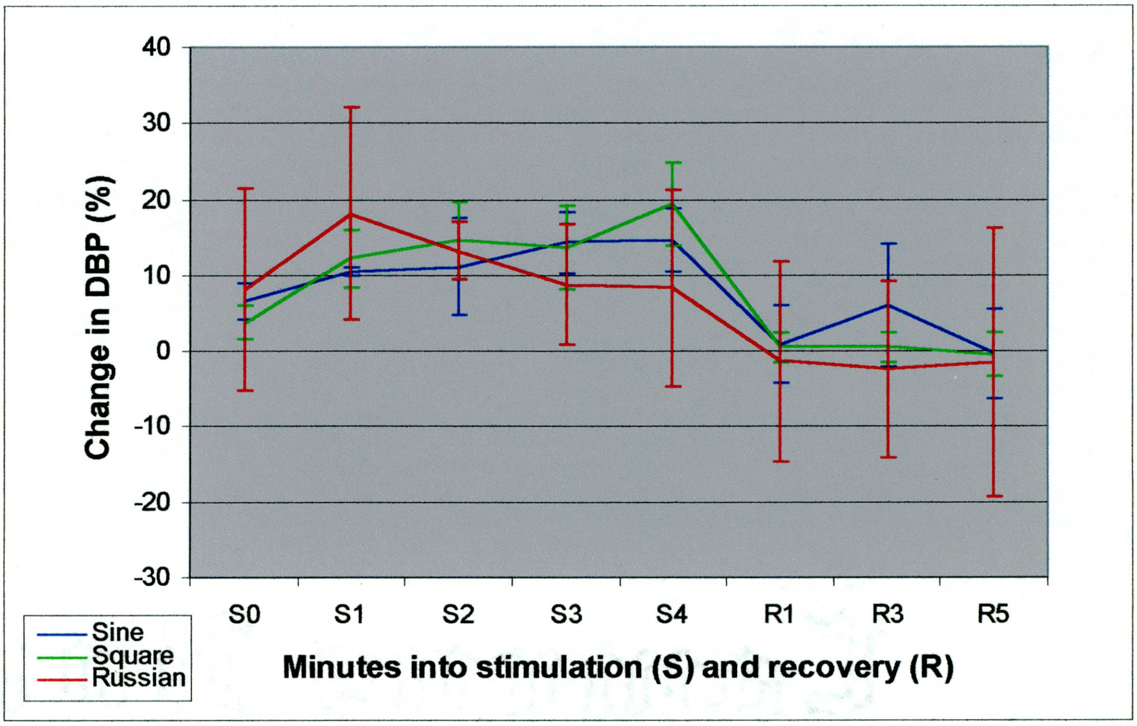

Figure 16. Mean change (%) from baseline in diastolic blood pressure (DBP) during the 4-minute contraction and 5-minute recovery period. Error bars indicate standard error.

Heart rate

The mean heart rate, as determined by measuring the distance between the peaks of the pulsatile blood flow wave visualized with the use of a photoelectric plethysmograph, did not demonstrate any significant changes during the 4-minute-long isometric contraction when within or among waveform measures were analyzed (p>0.05). Minimal differences in heart rate are seen in Figure 17 when stimulations utilizing the Russian, sine, and square waveforms were compared. The mean heart rate rise associated with the contractions elicited by the sine waveform stimulations were consistently higher than those utilizing either the Russian or square waveforms, but due to the large variability these differences were not statistically significant (p>0.05).

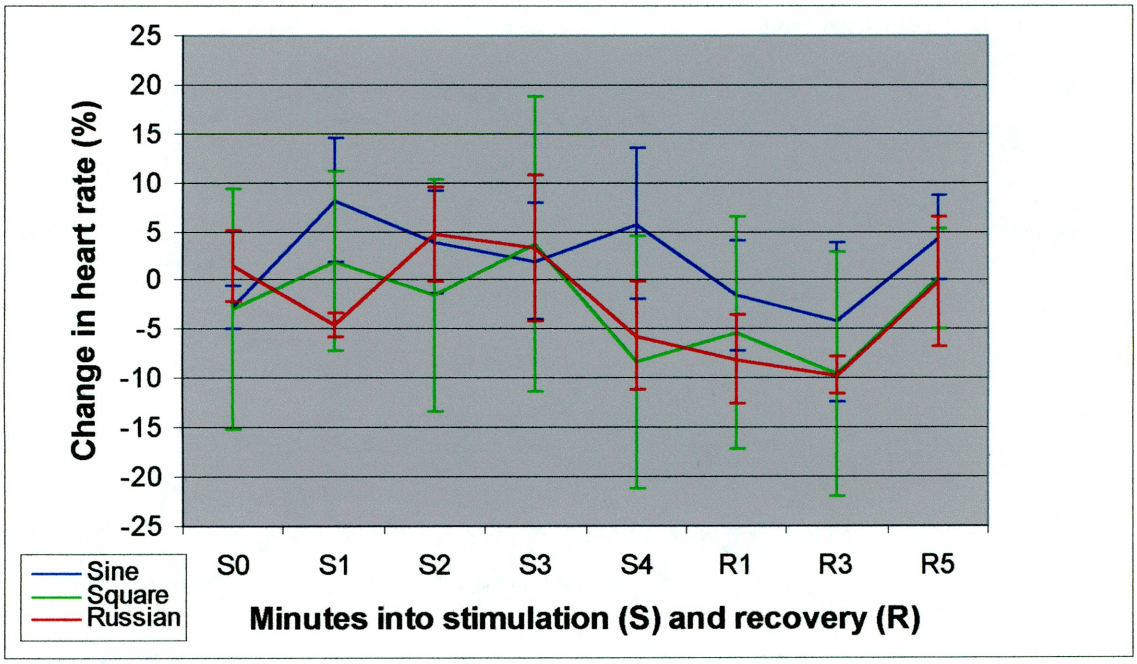

Figure 17. Mean change (%) from baseline in heart rate during the 4-minute contraction and 5-minute recovery period. Error bars indicate standard error.

Galvanic skin resistance

Galvanic skin resistance (GSR) determines changes in skin resistance as a measure of the sympathetic nervous system's response to painful stimuli. The stimulations using the Russian waveform caused a greater increase in GSR from the resting baseline measure to the one-minute mark than did those stimulations using either the sine or square waveforms, although the difference in increase was not significant (p>0.05). During the recovery period following stimulations with all three waveforms, the GSR decreased to a level below that of the baseline measure by greater than 50% as can be seen in Figure 18, but due to the large variability, the decrease was not significant (p>0.05). There were no significant differences in mean GSR change when within- or among-waveform measures were analyzed for the Russian, sine, and square waveforms.

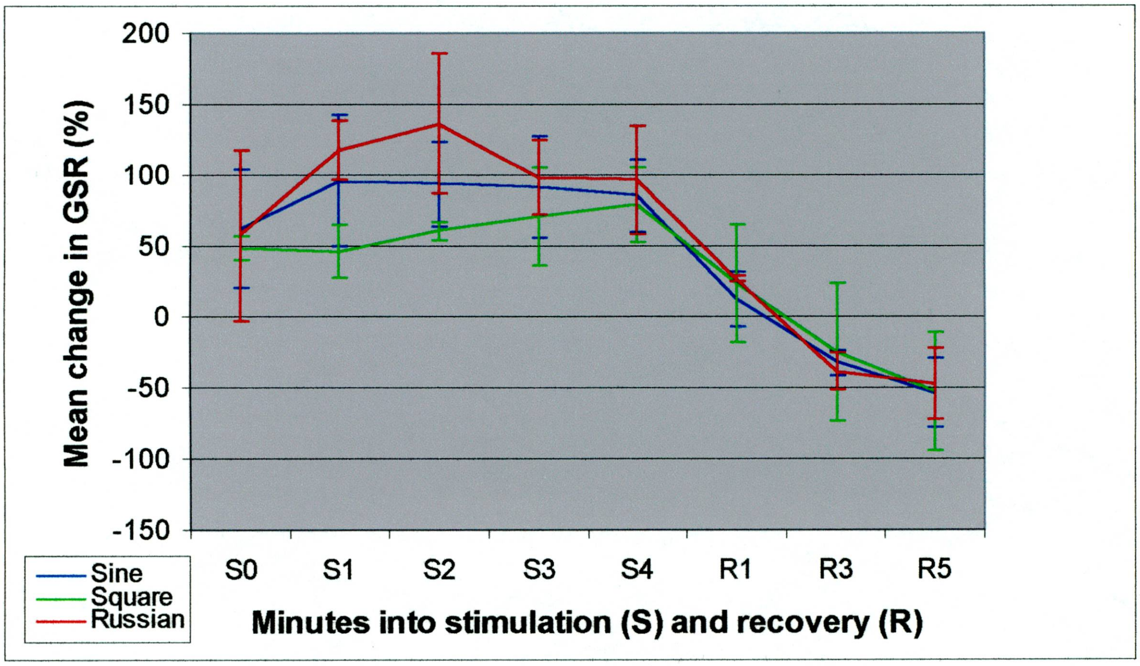

Figure 18. Mean change (%) from baseline in galvanic skin resistance (GSR) during the 4-minute contraction and 5-minute recovery period. Error bars indicate standard error.

Discussion

When the desired treatment goal for electrical stimulation is muscle strengthening, there are three major considerations when evaluating the effectiveness of the stimulation parameters: the mean stimulation current required to achieve a strong muscle contraction, the subjective comfort of the stimulation, and the physiological responses to the electrical stimulation. This study used four-minute-long electrically stimulated isometric contractions of the right quadriceps muscle with a force equal to 10% of the MVC to determine the effect of waveform on these three areas of interest.

The waveforms used in this study included Russian, interferential, sine, and square. A 200-μs pulse width was used during the contractions utilizing the Russian waveform, whereas a 100-μs pulse width was used for the interferential, sine, and square waveforms. The interferential waveform stimulation, even at full power, could not elicit an isometric contraction force equal to 10% of the force of the subject's MVC. Therefore, the interferential stimulation could not be included in the data analysis, except for comparison of the mean stimulation current variable. Detailed analyses were performed on the mean stimulation current, the subjective comfort, and the physiological responses recorded for the electrically stimulated contractions employing the Russian, sine, and square waveforms.

Mean stimulation current

In this study, the mean stimulation current required to elicit an isometric contraction of the quadriceps at 10% of the MVC was three times less when utilizing the sine waveform than when the square waveform was used, therefore producing less tissue trauma to the skin (DiVincenti et al. 1969). The stimulation with the Russian waveform produced 45 times the mean stimulation current used with the sine waveform, and the interferential produced over 120 times the current, thus dramatically increasing the possibility of an electrical burn. Increasing the safety of the electrical stimulation treatment by minimizing the mean stimulation current is especially important in clinical applications when using electrical stimulation on individuals with sensory deficits, as following a spinal cord injury (Hooker et al. 1995) or stroke. In this study, the sine waveform consistently required the lowest mean stimulation current to achieve the desired contraction force, making it the safest choice of the waveforms compared.

Subjective comfort

The ability to achieve the desired force of contraction with electrical stimulation is often limited by subjective complaints of discomfort. The subjective comfort scores on both the VAS and VRS were consistently lower during sine waveform stimulation than with the Russian or square waveforms. In fact, while the Russian and square waveform resulted in an increase in subjective discomfort over the duration of the 4-minute contraction, the stimulations that employed the sine waveform consistently had a decrease in subjective discomfort levels. Therefore, the results of this study suggest that the sine wave is the most comfortable waveform.

Objective measures - Physiological responses

Physiological responses during electrical stimulation may also vary with the choice of waveform. Based on a previous study by Spengler et al. (1994), the increases in V_E and VO_2 seen in this study were expected, however, the change in ventilation (V_E)

from rest differed among contractions employing the Russian, sine, and square waveforms. An increase in V_E and VO_2 has been previously reported during voluntary isometric exercise (Petrofsky 1982), thus the increase seen in this study can be attributed to the isometric exercise itself and does not appear to be a sympathetic response to pain. The changes in VCO_2 and RQ can also be attributed to the muscular contraction and not to the sympathetic outflow. Therefore, respiratory parameters reflect the effects of the isometric contraction and cannot be used as an objective measure of comfort when comparing electrical stimulation parameters. The timing of the increase in mean ventilatory change (between the 2- and 3-minute mark) is consistent with a previous report by Petrofsky (1982). This marked hyperventilation during isometric exercise is also consistent with previous studies by Wiley and Lind (1971) and Myhre and Andersen (1971), although those studies used voluntary contraction forces equal to 30% to 40% of the MVC. Following stimulation with the Russian, sine, or square waveform, the return of ventilation to baseline required approximately three minutes and did not occur without delay as has been suggested in previous texts (Petrofsky 1982). Following cessation of the sine waveform stimulation, the mean respiratory quotient decreased to 20% less than the original baseline resting value, signifying an increase in oxygen consumption throughout the recovery period, possibly to reduce the negligible oxygen debt previously suggested by Imms and Mehta (1989).

An increase in skin temperature was seen throughout the stimulated contractions utilizing the Russian, sine, and square waveforms at each of the three measured points: under the stimulating electrode on the right quadriceps muscle, on the left quadriceps muscle, and on the forehead. These findings are consistent with previous research in which both ipsilateral and contralateral increases in skin temperature were seen following subthreshold transcutaneous electrical nerve stimulation (TENS) (Abram et al. 1980) and following static voluntary contractions of the opposite quadriceps muscle (Gaffney et al. 1990). Abram et al. (1980) and Owens et al. (1979) suggest that this increase in skin temperature is associated with diminished sympathetic tone. Therefore, the increase in skin temperature under the electrode during the sine waveform stimulations represents the greatest reduction in sympathetic tone, signifying the greatest objective comfort.

Interestingly, a post-exercise hyperemia was noted at the forehead following contractions using the Russian, sine, and square wave stimulation. Petrofsky (1982) suggests three possible mechanisms that control this hyperemia during isometric exercise: metabolic control, myogenic control, and neurogenic control. Metabolic control, due to the release of metabolites from the contracting muscle, cannot be ruled out based on the results of the current study. Myogenic control of blood flow is due to the increased intramuscular pressure during the isometric contractions, although with the 10% MVC elicited in this study, the intramuscular pressure rise would be minimal (Petrofsky and Hendershot 1984) and can therefore be excluded as the cause of the post-exercise hyperemia. Neurogenic control arising from the sympathetic nervous system can also be ruled out as the cause of the hyperemia. The hyperemia occurred following cessation of the uncomfortable electrical stimulation when the sympathetic nervous system was no longer receiving a noxious stimulus, and thus, was no longer activated. Therefore the hyperemia noted in this study may be attributed to the release of metabolites from the active muscle. As in a study by Currier et al. (1986), blood flow, measured at the forehead in the current study, increased in the first minute of the electrically stimulated contraction. The notable rise in skin temperature and blood flow, both locally and systemically, signifies an increase in circulation and a superficial vasodilation. This finding supports the use of electrical stimulation for increasing blood flow in individuals with circulatory deficits including, but not limited to, peripheral vascular disease (PVD) (Loubser et al. 1988), to reduce the pharmacologic and surgical interventions that are the mainstays of treatment for PVD, and to reduce the cost and healing times of pressure sores (Petrofsky 2000).

As in a study by Lind and McNicol (1967), the results of this study indicated an initial rise in systolic and diastolic blood pressure over the first quarter (1-minute) of the contraction time followed by the achievement of a steady state that appears equivalent to the tension of the contraction (Petrofsky 1982). The mean blood pressure and heart rate rise seen in this study involving electrically stimulated isometric contractions was similar to previous studies that involved voluntary isometric contractions, thus ruling out the electrical stimulation and the studied waveforms as the cause of the changes in blood pressure and heart rate (Lind and McNicol 1967; Petrofsky 1982). The minimal increase in mean heart rate during the 4-minute-long electrically stimulated isometric contraction suggests that previous studies implicating a centrally mediated heart rate response are correct (Freyschuss 1970; Funderburk et al. 1974).

The mean increase in galvanic skin resistance (GSR) from baseline throughout the entire stimulation period was consistently greater during the contractions elicited by electrical stimulation using the sine wave than those stimulations utilizing the square waveform. This increase in resistance suggests a diversion of the blood flow from the measured area (index and middle fingers, ipsilateral side of contraction) due to the vasoconstrictive response of the sympathetic nervous system. Following cessation of the stimulated contractions, GSR decreased to levels approximately 50% below the initial resting baseline. This decrease in resistance is attributable to the post-exercise hyperemia and resultant increase in perspiration. In spite of the greater measured sympathetic activity during the stimulations using the sine wave than during the square wave stimulation, the contractions employing the sine wave were subjectively less painful. Due to the sample size (n=7), correlation of the subjective (VAS and VRS) and objective (GSR) measures of discomfort was not possible. Further study is recommended for correlation of subjective and objective measures of discomfort during electrically stimulated contractions.

Conclusion

An ideal waveform minimizes the mean stimulation current required to achieve the desired goal, which in this study was to facilitate a good muscular contraction, while maximizing subjective and objective comfort. Russian, sine, and square wave stimulations elicited the desired force of contraction equally well, whereas the interferential current was unable to elicit the desired contraction force. In this study, the stimulations using the sine waveform required much less mean stimulation current than the other waveforms, thus minimizing the trauma to the tissue. The stimulations using the sine waveform also resulted in dramatically better subjective and objective measures of comfort. In conclusion, the sine waveform is recommended over the Russian, interferential, and square waveforms when desiring to stimulate isometric contractions that cause the least tissue trauma to the skin with the greatest subjective and objective comfort for the patient.

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Appendix I.

Literature Review

Literature Review

Rehabilitation professionals use several different forms of electrical stimulation (ES) in clinical practice to address many diverse patient needs. The rate of healing in chronic wounds, specifically pressure sores, improves with electrical current when natural healing mechanisms of the body are insufficient (Petrofsky 2000; Stefanovska 1993).

Clinicians use neuromuscular electrical stimulation (NMES) to strengthen healthy muscle with (McMiken et al 1983; Selkowitz 1985) and without (Godfrey et al. 1979; Laughman et al. 1983) simultaneous voluntary contraction. Strength training programs for individuals with chronic heart failure are used to address the marked skeletal muscle weakness common to the diagnosis (Quittan et al. 1999). Electrical stimulation reduces muscular atrophy (Eriksson and Häggmark 1979), and is used postoperatively to strengthen muscle (for example, following anterior cruciate ligament reconstruction (Snyder-Mackler et al. 1991; Snyder-Mackler et al. 1995)), and to return the patient to the highest possible functional level.

Transcutaneous electrical nerve stimulation (TENS) and NMES individually are shown to reduce chronic back pain, and when combined produce significantly greater results than when TENS or NMES are use alone (Moore and Shurman 1997). Chronic pain of more diverse etiologies also diminishes with TENS intervention (Loeser et al. 1975; Repperger et al. 1997). Pain from diabetic peripheral neuropathy has been significantly reduced using TENS (Kumar and Marshall 1997).

Research supports the use of electrical stimulation in many specific patient populations. Muscle tone in individuals with spinal cord injuries (SCI) has been nearly normalized following two-month-long NMES training programs (Douglas et al. 1991). Cardiorespiratory fitness in the SCI population can also be significantly improved with a 30-minute NMES leg cycle training program performed at least twice weekly (Hooker et al. 1995). Individuals with upper extremity hemiplegia benefit from electrical stimulation with increased wrist extensor strength, and improvement in their functional capabilities (Powell et al. 1999). Additionally, range of motion gains are demonstrated when positional feedback mechanisms are integrated into the hemiplegic's rehabilitation plan (Bowman et al. 1979). Lower extremity hemiplegic patients have responded to electrical stimulation to facilitate normalized gait patterns (Liberson et al. 1960). Correction of footdrop has been made possible with the use of electrical stimulation (Waters et al. 1975). Upper extremity spasticity is decreased when NMES is combined with the use of dynamic bracing in children with cerebral palsy (Scheker et al. 1999). The commonly seen equinovarus in the same population can also be managed by strengthening the triceps surae muscle utilizing electrical stimulation (Carmick 1995). Excessive kyphotic and scoliotic spinal curvatures have been successfully managed with the use of electrical stimulation (Axelgaard et al. 1983).

Attempts to increase the amplitude or intensity of ES are often limited by subjective complaints of discomfort. In an effort to minimize discomfort, many studies have attempted to determine which parameters, or combination of parameters, caused the least patient discomfort. Individual waveform preference was found when sinusoidal, triangular, and square waves were compared for their relative subjective comfort levels during ES of the quadriceps muscle (Delitto and Rose 1986). A symmetric biphasic square waveform was generally preferred for the large quadriceps muscle group, whereas an asymmetric biphasic square waveform was preferred for the smaller forearm musculature when compared to a monophasic paired spike and three medium frequency waveforms (Baker et al. 1988). Individual preferences also seem to occur when burst and carrier frequency modes are compared for comfort (Rooney et al. 1992).

Changes in frequency seem to have an effect on torque production. By increasing the frequency, greater comfort is achieved with a resultant decrease in torque production. Torque production is increased when lower frequencies (<1KHz) of alternating current are used. It is suggested that 50 Hz creates a balance between comfort and torque production (Ward and Robertson 1998). Increasing the frequency does, however, increase the rate of muscular fatigue (Binder-Macleod and Anderson 1992). Muscular fatigue from electrically stimulated contractions is also affected by the duty-cycle, where a 1:5 (on:off) ratio has been found to be optimal (Packman-Braun 1988). Generally, the greater the amplitude of the stimulation, the stronger the muscle contraction due to the recruitment of more motor units (Selkowitz 1985). Achieving strength gains in muscle depends on having sufficient intensity of the stimulated muscle contraction to stress the muscle (Selkowitz 1985). But intensity is often limited in both research and clinical settings by subjective complaints of discomfort.

Electrode size also affects subjective comfort during ES. Greater voltage output is required when electrode size is increased, but there is less phase charge density when compared to smaller electrodes (Alon 1985). Comfort of stimulation to facilitate a contraction of equal force is improved when electrode size is increased (Alon et al. 1994). Electrode type has also been compared, with carbonized conductive silicone rubber electrodes found to be more suitable for prolonged stimulation of the quadriceps muscle than self-adhering pre-gelled pads, solvent-activated conductive tape, or felt-covered metal plates (Nelson et al. 1980).

The International Association for the Study of Pain gives the definition of pain as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage." The Academic Press Dictionary of Science Technology (1995) defines pain as, “a relatively localized sensation of discomfort, distress, or agony, resulting from the stimulation of specialized nerve endings”. The visual analog scale (VAS) and the verbal rating scale (VRS) have been used in many of the previously noted studies as an index to measure subjective discomfort. Although the VAS (Price et al 1983) and the VRS (Downie et al. 1978) are valid, they make the variable of discomfort in these studies wholly subjective. Clinically, it is difficult to ascertain whether a patient’s subjective report of 8/10 pain on the VRS one week is comparable to a similar score at a later time. Therefore, objective, valid, and reliable measures of pain have been sought.

In an effort to objectively quantify the optimum waveform and stimulation parameters, physiological responses have also been studied. Changes in blood flow during ES application have varied among studies, although significant increases in skin temperature have been noted both ipsilaterally and contralaterally following sub-motor threshold TENS of 20 to 45 minutes in duration (Abram et al. 1980). Dramatic increases in temperature under the electrode due to current flow, however, can cause tissue damage by dramatically decreasing the ph at the skin, leading to burns involving cutaneous and even subcutaneous tissues (DiVincenti et al. 1969). These electrically induced burns have been studied both in animal experimental studies (Sances et al. 1981) and in human case studies following functional electric stimulation use (Balmaseda et al. 1987).

A contralateral increase in limb blood flow has been seen briefly following a static voluntary contraction of the opposite quadriceps muscle (Gaffney at al. 1990). Significant increases in superficial blood flow have been noted following 60 minutes of unilateral, low frequency NMES in subjects with peripheral vascular disease (Loubser et al. 1988). Blood flow, as measured by a Doppler device, increased in the first minute of an electrically stimulated isometric contraction equal to 10% of MVC (Currier et al. 1986). These findings differ from other studies in which no significant limb blood flow changes were noted with intensities either above or below motor threshold (Indergand and Morgan 1994). Neuromuscular ES can be used to increase microvascular perfusion of the stimulated muscle (Clemente et al. 1991), but the intensity should be increased to a level to stimulate a muscle contraction (Clemente and Barron 1993). Positron emission tomography has shown that the greatest increases in blood flow occur in the muscles closest to the electrode, with a proportional decrease in flow as distance from the electrode increases. (Vanderthommen et al. 2000).

The responses of systolic and diastolic blood pressures to isometric exercise, voluntary and involuntary, fatiguing and non-fatiguing, have been studied frequently.

During fatiguing and non-fatiguing voluntary isometric exercise, a linear rise in systolic and diastolic blood pressures occurs over time (Davies and Starkie 1985). It is suggested that the cause of the rise in blood pressures in response to isometric exercise is the release of a metabolite, possibly potassium, from the isometrically contracting muscles that stimulate type III and IV sensory fibers (Lind et al. 1964; Hnik et al. 1969), which in turn cause a splanchnic sympathetic vasoconstriction (Petrofsky 1982). During the fatiguing isometric contractions, those contractions above 15% of the maximal voluntary contraction (MVC) force, a continuous increase in blood pressures are seen throughout the duration of the contraction (Lind et al. 1964; Funderburk et al. 1974). The non-fatiguing isometric contractions result in a rise in blood pressures that is proportional to the tension exerted by the contracting muscles (Petrofsky 1982). If the isometric contractions are maintained at these non-fatiguing tensions (<15% MVC), the blood pressures achieve a steady state following the initial rise (Lind and McNicol 1967). Similar increases in systolic and diastolic blood pressures occur during involuntary, or electrically stimulated, isometric contractions (Davies and Starkie 1985).

Heart rate response to voluntary isometric contractions at non-fatiguing tensions are similar to BP changes in that there is only a small increase in heart rate that attains a steady state after approximately two minutes (Lind and McNicol 1967). The change in heart rate, although less dramatic than the pressor response, is still significant (Mitchell et al. 1977; Schibye et al. 1981). During fatiguing voluntary isometric exercise, the heart rate does increase, but rarely exceeds 120 beats per minute (Lind et al. 1964). Following voluntary fatiguing isometric contractions, the heart rate is directly proportional to the tension developed by the muscles (Funderburk et al. 1974). Voluntary isometric contractions cause a greater increase in heart rate than involuntary, or electrically stimulated isometrics (Davies and Starkie 1985; Goldberg et al. 1982). Many studies suggest that the heart rate response is centrally mediated (Coote et al. 1971; McCloskey and Mitchell 1972), unlike the aforementioned blood pressure response, which is more peripherally mediated.

Ventilation (V_E) has been shown to increase during voluntary isometric exercise (Mitchell et al. 1977) due to a rise in tidal volume and a reduction in expiratory duration (Paulev et al. 1991). In electrically induced rhythmic-static single leg exercise, a significant initial rise in V_E and oxygen uptake (VO_2) was noted, followed by achievement of a steady state (Spengler et al. 1994). There was a greater correlation between these two variables, V_E and VO_2, during electrically stimulated contractions than during voluntary isometric exercise (Spengler et al. 1994).

The crossed extension reflex, associated with the flexor withdrawal reflex, is commonly known and accepted to be a normal reflexive response to a painful stimulus. This has been studied and substantiated in response to painful electrical stimuli in man (Arendt-Nielson et al. 2000). The body's sympathetic responses to pain can be measured by monitoring changes in skin resistance due to perspiration with the use of galvanic skin resistance (Danilov et al. 1994).

A study that will relate force developed in muscle during electrical stimulation to many of the aforementioned parameters in an attempt to assess and possibly correlate subjective and objective responses is necessary. The study should provide a comprehensive examination of subjective, objective, and physiological responses to electrically stimulated isometric contractions utilizing different waveforms.

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Appendix II.

Series 1 Methods and Results

Series 1 Methods

Four males and three females received 14 bouts of electrical stimulation to produce a 10-second isometric contraction force of the right quadriceps muscle that was equal to10% of their MVC. The order of application of the 14 combinations of parameters was randomized. The waveforms used included interferential, Russian, sine, and square. The two frequencies used were 30 and 60 pulses per second (pps) for the square, sine, and interferential waveforms while 20% and 50% duty cycles were used for the Russian stimulation. Pulse widths were 100 and 500 microseconds (μs) for square and sine waveforms, 200 and 500 microseconds (μs) for the Russian stimulation, and 100 microseconds (μs) for the interferential. Series 1 was performed in its entirety at the beginning of each day of data collection. It is necessary to note that when the interferential waveform was utilized during the stimulations, a contraction force equal to 10% of the MVC was unattainable. Also, one subject completed only the first day of data collection.

Following each of the contractions, VAS and VRS subjective pain measures were obtained without subjects' access to their previous ratings. A one-minute rest was given between each of the contractions.

Series 1 Results

Mean stimulation current

The mean current required to electrically stimulate a 10-second-long isometric contraction force equal to 10% of the maximal voluntary contraction (MVC) with the pulse width set at 100-µs, was not significantly different when the sine and square waveforms were compared ($p>0.05$). Even though a force of 10% of the MVC could not be reached, the stimulations utilizing the interferential waveform required significantly greater ($p<0.001$) mean stimulation current than either the sine or square waveforms (Figure 19). The mean stimulation current was not significantly different ($p>0.05$) when the 30- and 60-pps frequencies were compared.

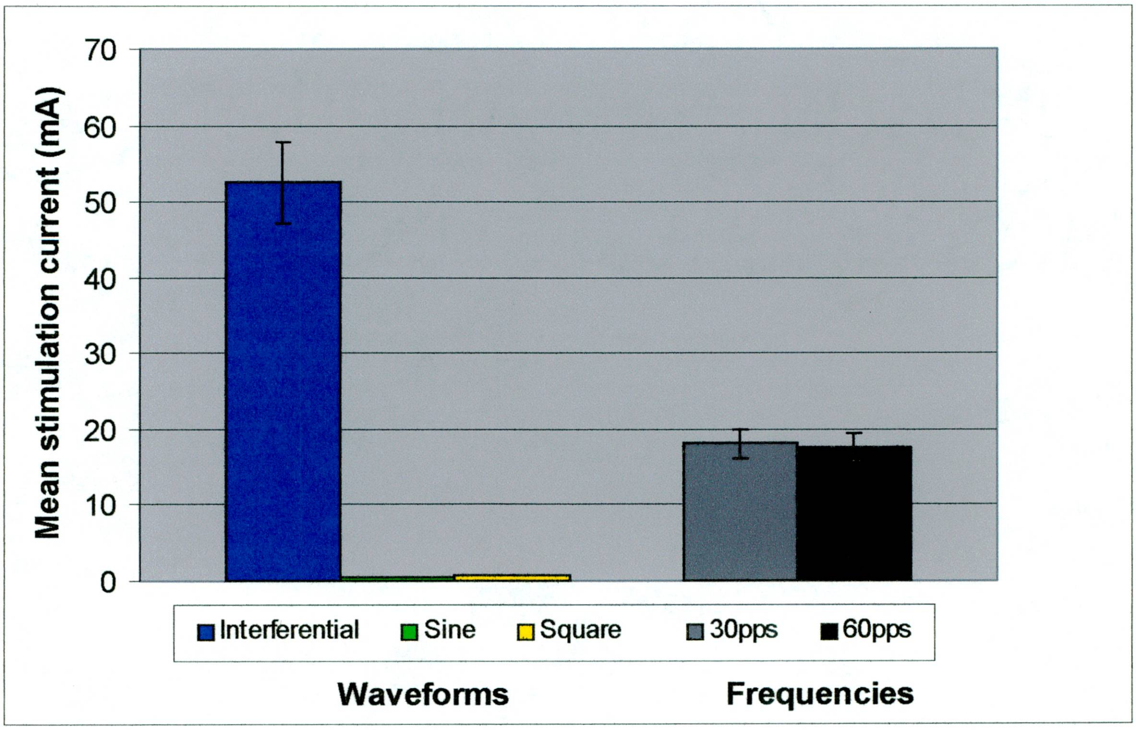

Figure 19. Mean stimulation current (mA) required to stimulate 10-second isometric contractions. Only sine and square waveforms were able to elicit an isometric force equal to 10% MVC using a 100-µs pulse width. Error bars indicate standard error.

The stimulations employing the Russian waveform required significantly greater ($p<0.001$) mean stimulation current to achieve the desired isometric contraction force than either the sine or square waveforms, as Figure 20 clearly displays, when the pulse width was maintained at 500-μs. Changes in frequency (30- and 60-pps) did not significantly affect the mean stimulation current required to induce the contraction force equal to 10% of the MVC ($p>0.05$).

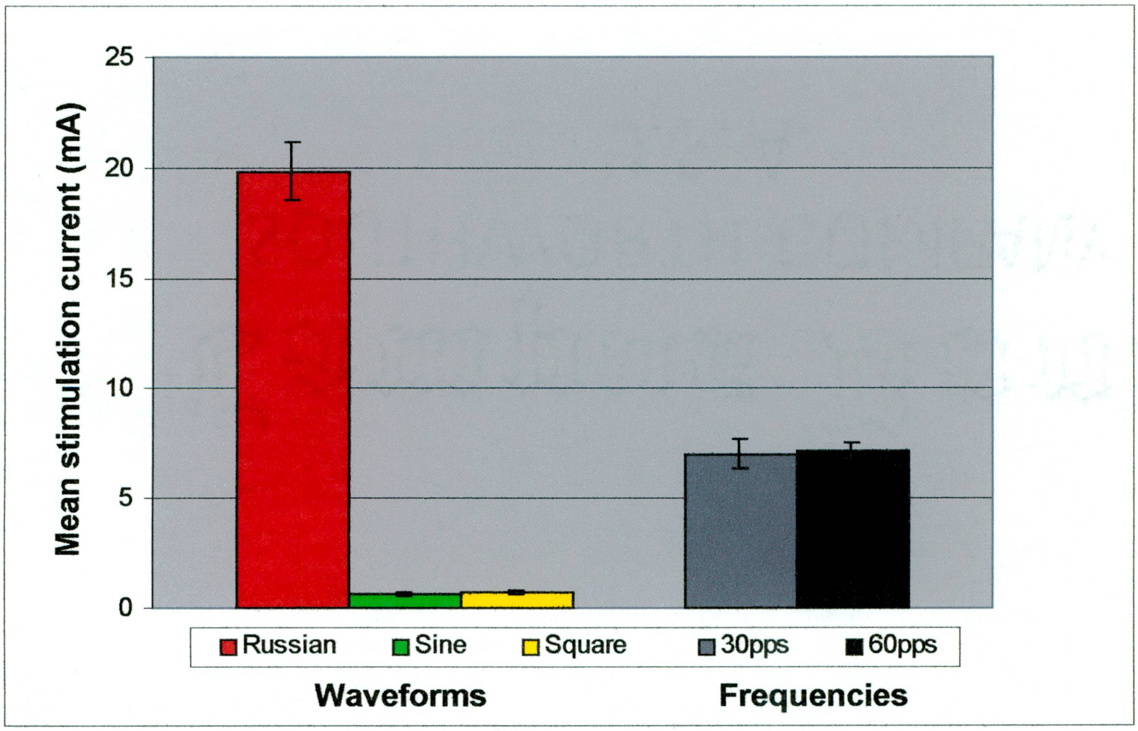

Figure 20. Mean stimulation current (mA) required to stimulate 10-second isometric contractions equal to 10% MVC using a 500-μs pulse width. Error bars indicate standard error.

Visual analog scale (VAS)

The mean visual analog scale (VAS) scores reported following each of the contractions using a 100-μs pulse width were not significantly different (p>0.05) when either the sine or square waveforms were employed (Figure 21). Changes in frequency (30- and 60-pps) did not significantly affect the VAS score after induction of a stimulated contraction force equal to 10% of the MVC (p>0.05).

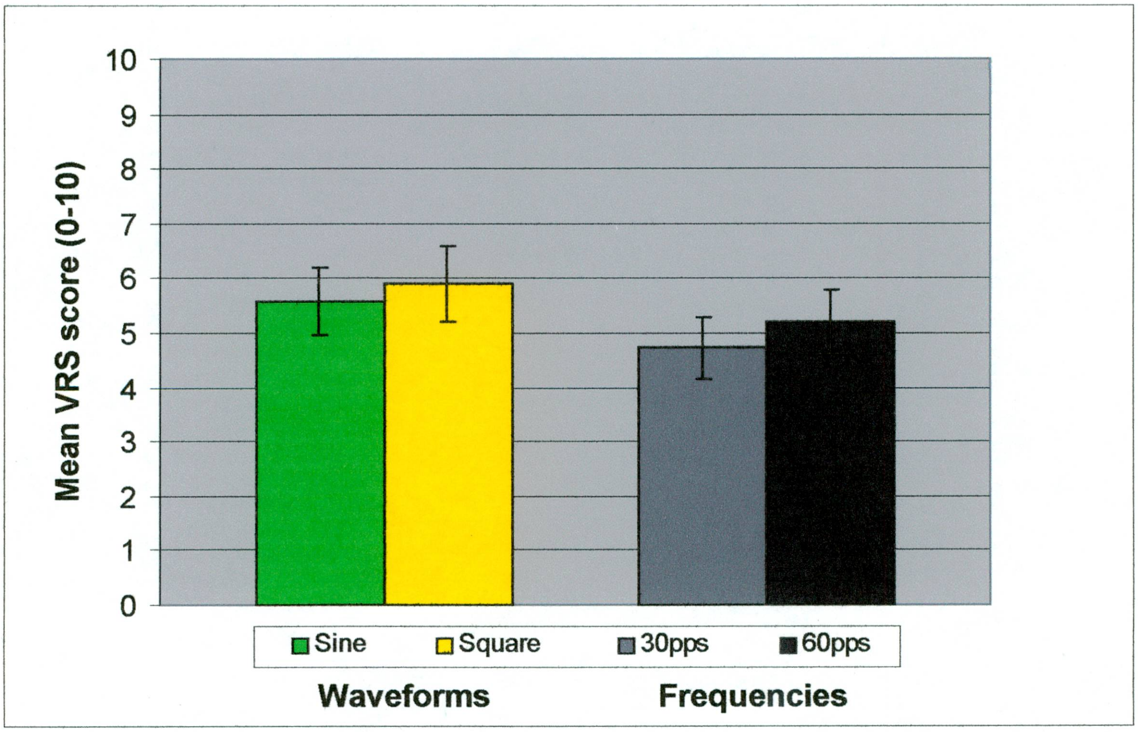

Figure 21. Mean visual analog scale (VAS) scores during the 10-second contractions equal to 10% MVC using a 100-μs pulse width. Error bars indicate standard error.

Figure 22 shows that at a 500-μs pulse width, the mean visual analog scale (VAS) scores for the contractions employing the sine waveform (4.59 ± 0.52) were significantly lower (p=0.008) than those using the Russian waveform (5.96 ± 0.62) although not significantly different from the stimulations employing the square waveform (4.92 ± 0.64). Changes in frequency (30- and 60-pps) did not significantly affect the VAS score after the stimulated contraction force equal to 10% of the MVC was elicited (p>0.05).

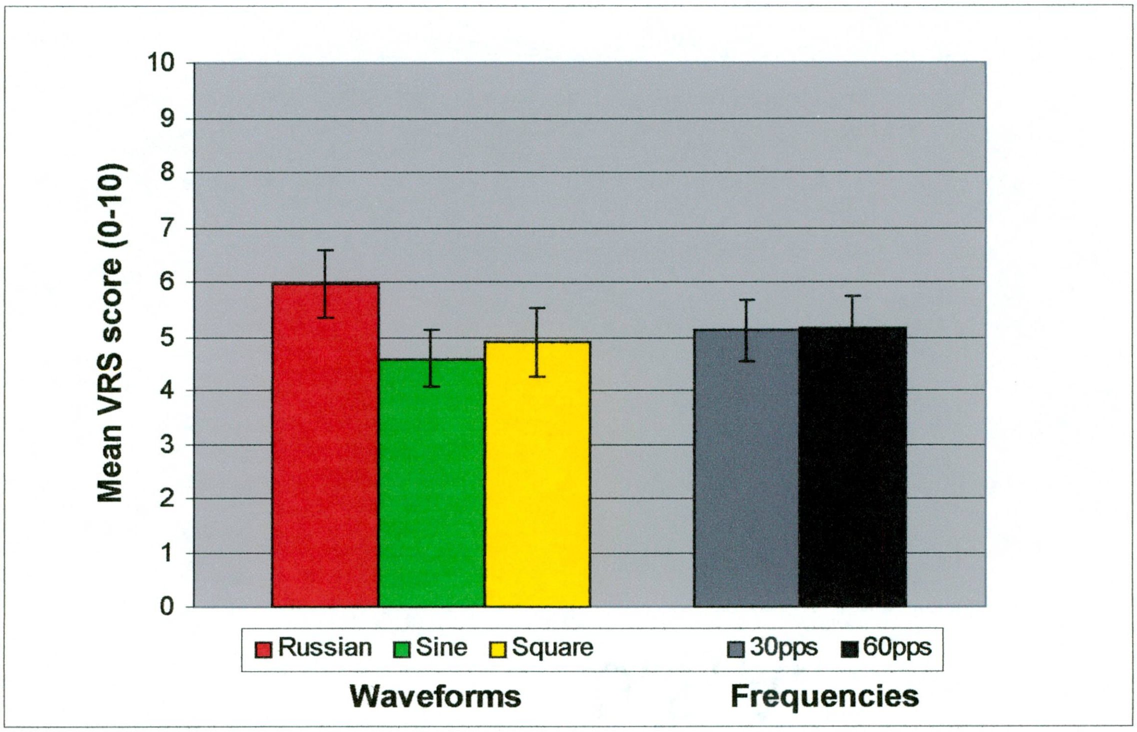

Figure 22. Mean visual analog scale (VAS) scores during the 10-second contractions equal to 10% MVC using a 500-μs pulse width. Error bars indicate standard error.

Verbal rating scale (VRS)

The difference in mean VRS scores between the Russian, sine, and square waveforms following each of the electrically stimulated isometric contractions using a 100-µs pulse width was not significant ($p>0.05$) (Figure 23). Frequency changes (30- and 60-pps) did not significantly affect the mean VRS scores after the generation of a stimulated contraction force equal to 10% of the MVC ($p>0.05$).

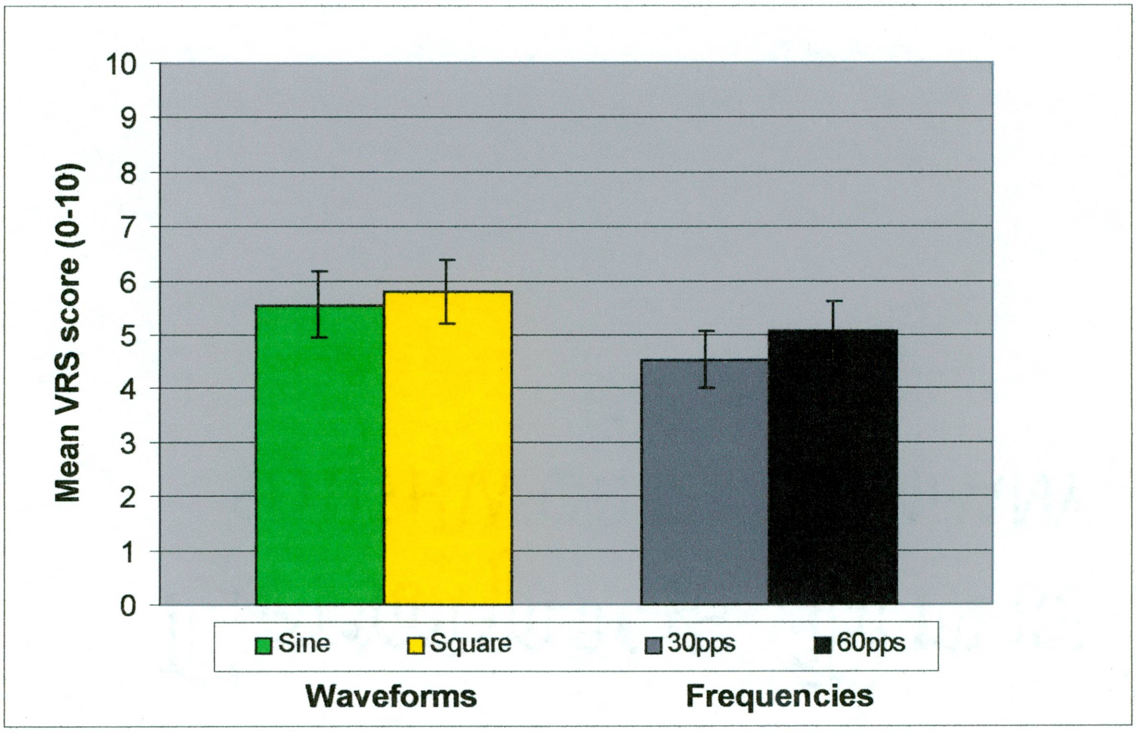

Figure 23. Mean verbal rating scale (VRS) scores during the 10-second contractions equal to 10% MVC using a 100-µs pulse width. Error bars indicate standard error.

The mean verbal rating scale (VRS) scores for the contractions employing the sine waveform (4.44 ± 0.49) were significantly lower (p=0.005) than those using the Russian waveform (5.71 ± 0.59) when the pulse width was maintained at 500-μs, as shown in Figure 24, but not significantly different than the square waveform (4.93 ± 0.60). Changes in frequency (30- and 60-pps) did not significantly affect the VRS scores when a contraction force equal to 10% of the MVC was stimulated (p>0.05).

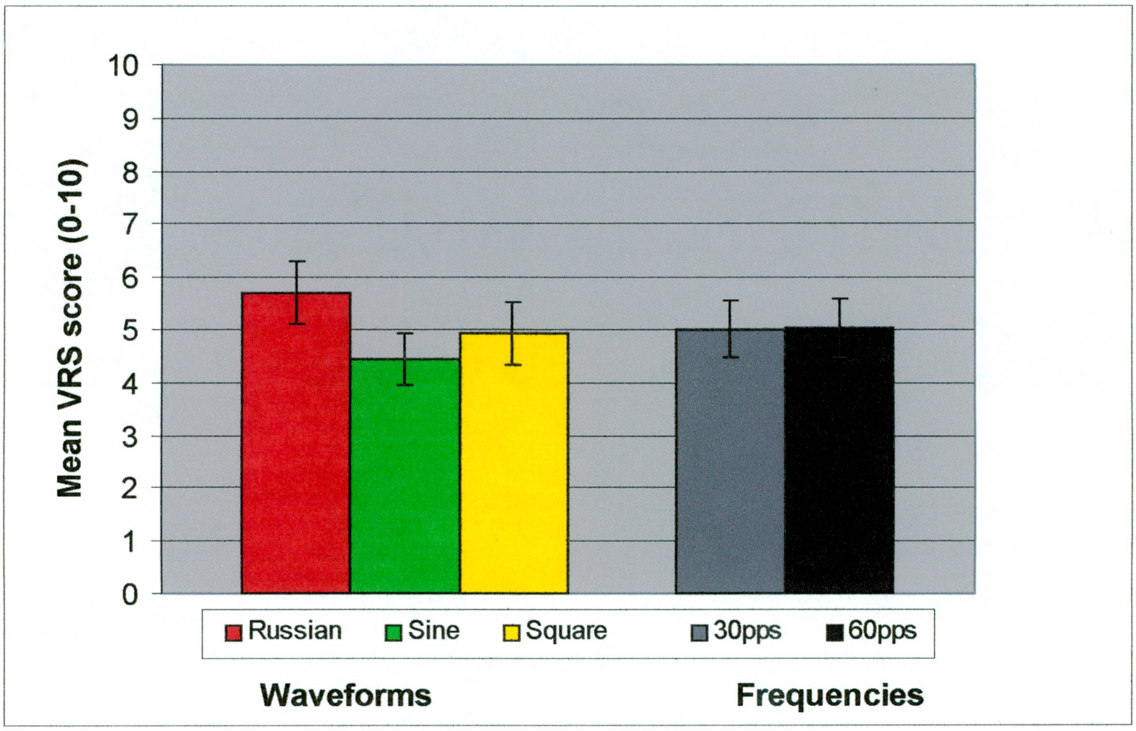

Figure 24. Mean verbal rating scale (VRS) scores during the 10-second contractions equal to 10% MVC using a 500-μs pulse width. Error bars indicate standard error.

Skin temperature. Skin temperatures were measured under the proximal stimulating electrode, on the opposite quadriceps muscle, and on the forehead of each subject before and during each electrically stimulated 10-second-long isometric contraction of the right quadriceps muscle. No significant changes from baseline in mean skin temperature were noted at any of the locations measured during this study when either waveform or frequency was analyzed (p>0.05). Figures 25 through 30 demonstrate the similar responses in skin temperature rise from baseline when comparing different waveforms at both the 100 and 500-μs pulse widths.

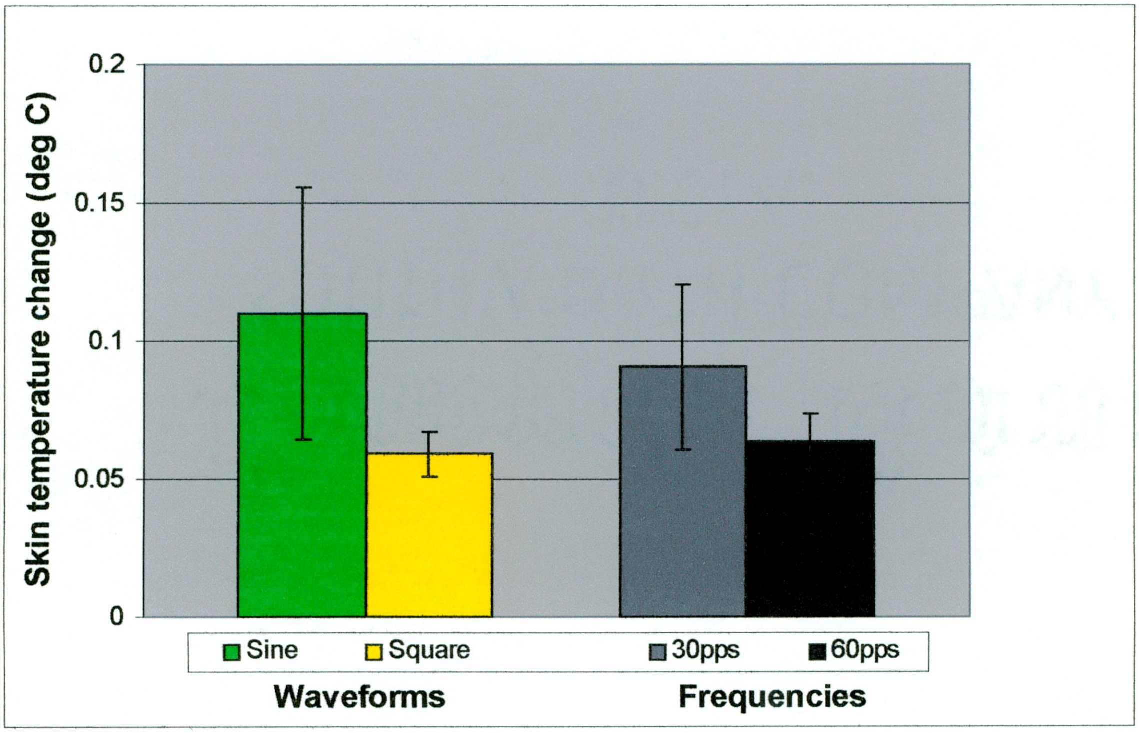

Figure 25. Mean change (°C) from baseline in skin temperature at the forehead during the 10-second contractions equal to 10% MVC using a 100-μs pulse width. Error bars indicate standard error.

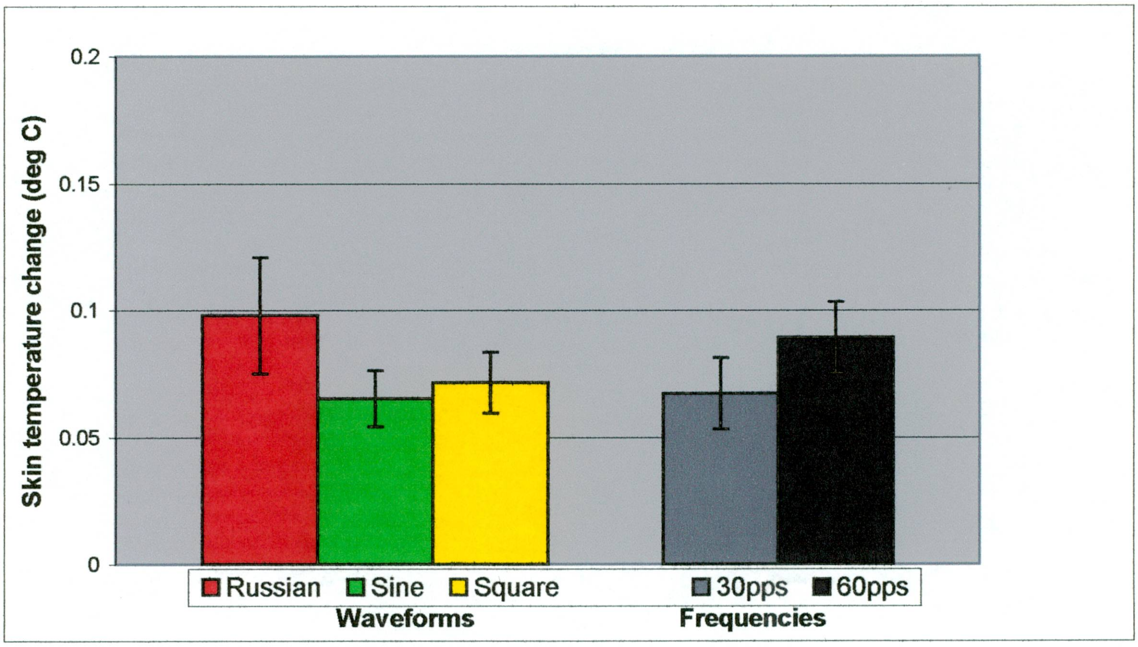

Figure 26. Mean change (°C) from baseline in skin temperature at the forehead during the 10-second contractions equal to 10% MVC using a 500-µs pulse width. Error bars indicate standard error.

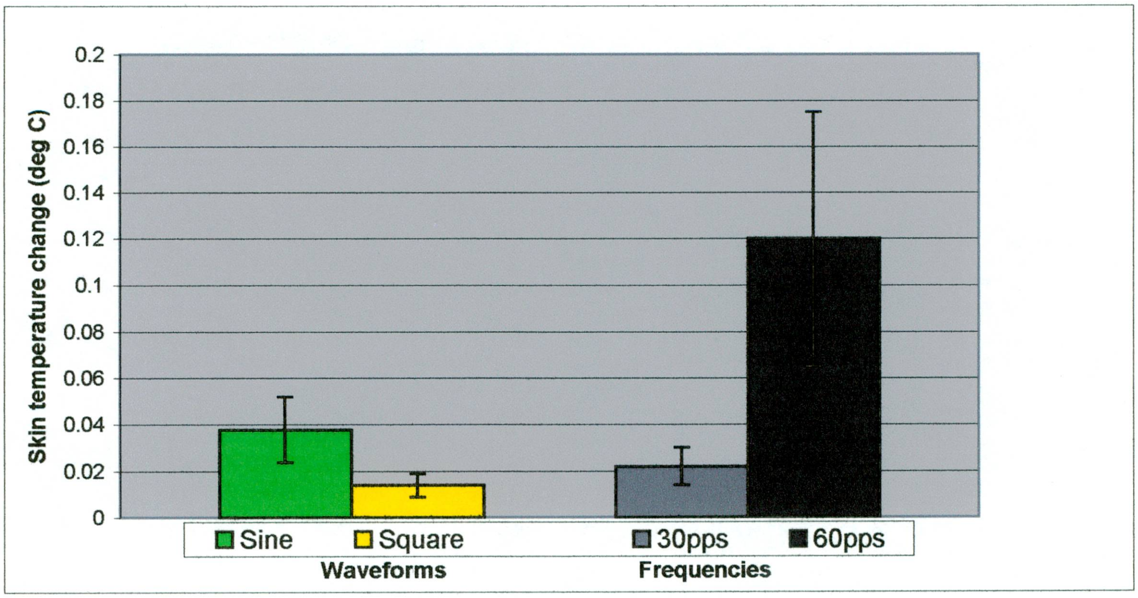

Figure 27. Mean change (°C) from baseline in skin temperature at the left quadriceps muscle during the 10-second contractions equal to 10% MVC using a 100-µs pulse width. Error bars indicate standard error.

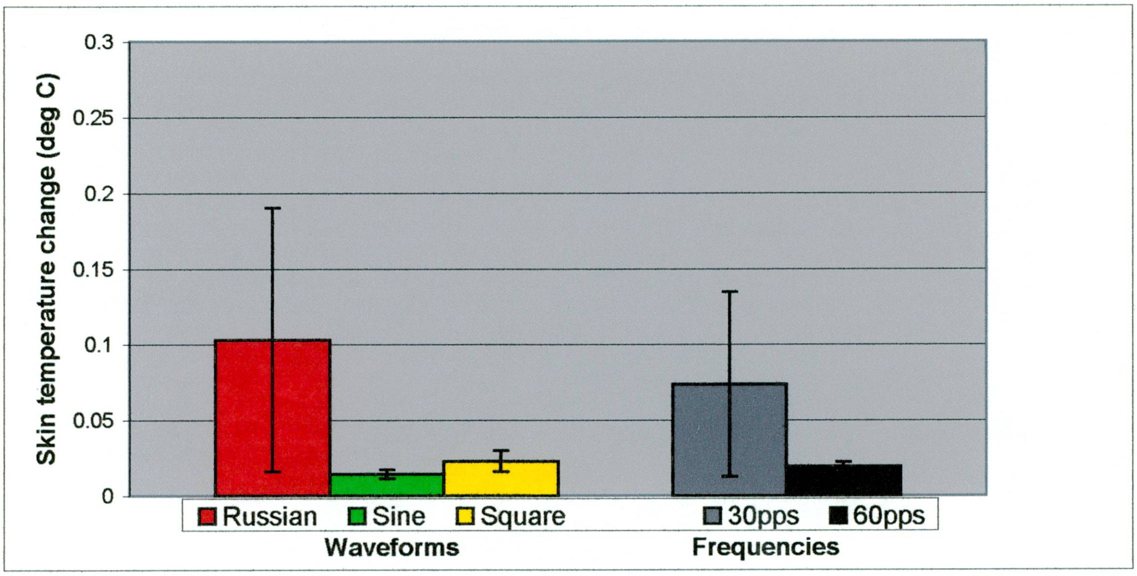

Figure 28. Mean change (°C) from baseline in skin temperature at the left quadriceps muscle during the 10-second contractions equal to 10% MVC using a 500-μs pulse width. Error bars indicate standard error.

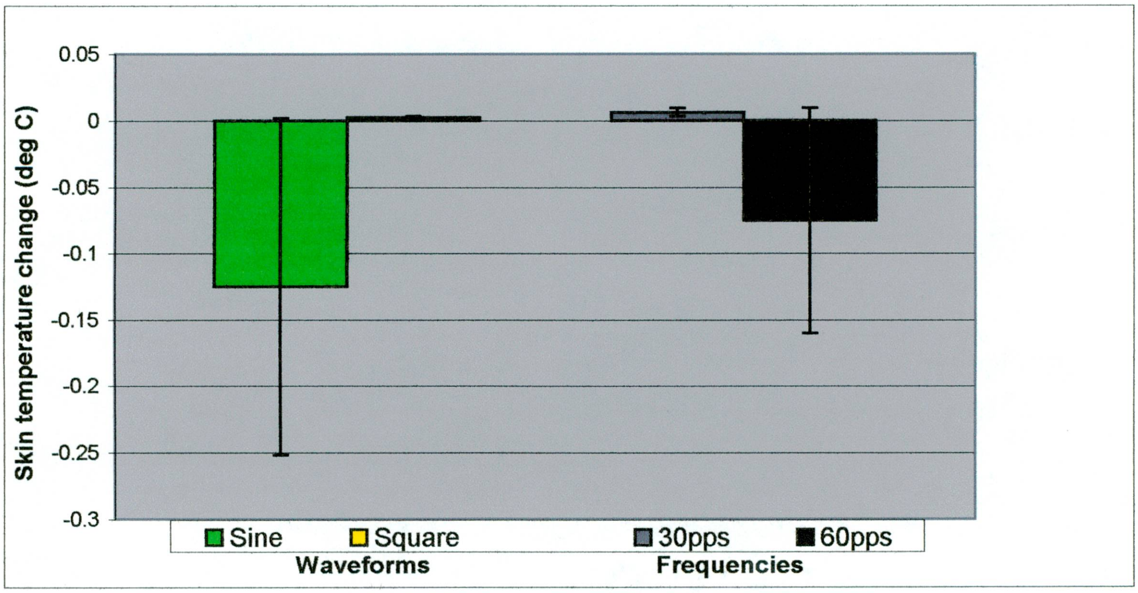

Figure 29. Mean change (°C) from baseline in skin temperature under the electrode during the10-second contractions equal to 10% MVC using a 100-μs pulse width. Error bars indicate standard error.

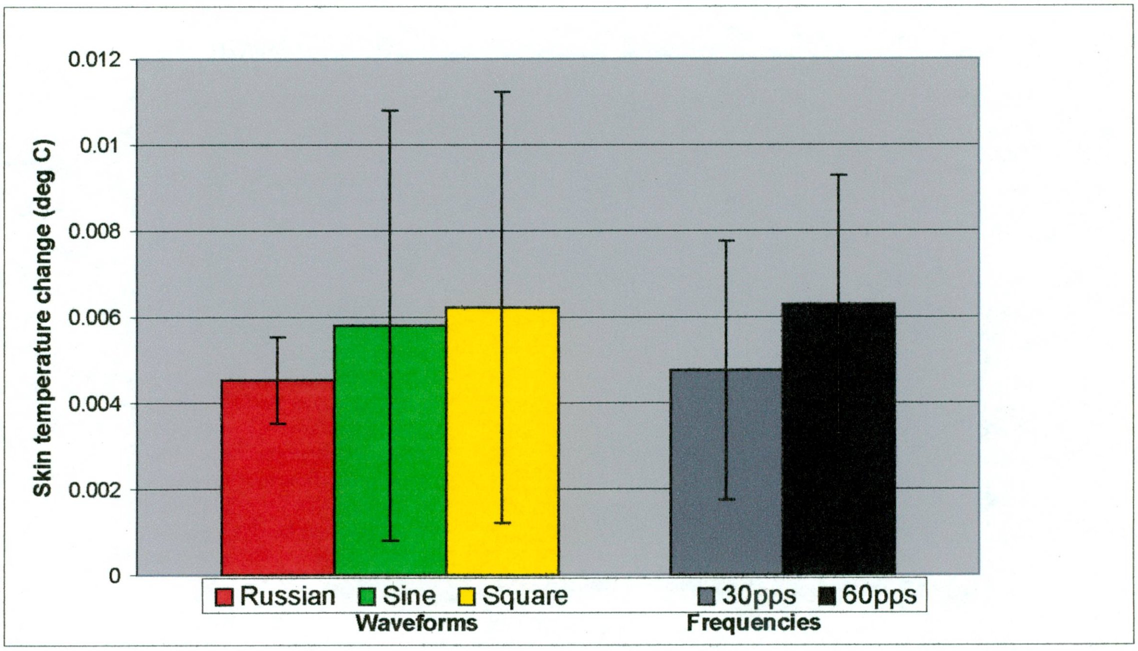

Figure 30. Mean change (°C) from baseline in skin temperature under the electrode during the 10-second contractions equal to 10% MVC using a 500-μs pulse width. Error bars indicate standard error.

Galvanic skin resistance

The mean galvanic skin resistance change from baseline during the electrically stimulated 10-second isometric contractions was analyzed. Figure 31 shows the mean increase for the three waveforms and for both frequencies when the pulse width was maintained at 100-μs. The mean change in GSR was not significant when waveforms or frequencies were compared (p>0.05) due to the large variability. However, the greatest increase (>100%) in mean GSR change from baseline was seen when utilizing square waveform stimulation.

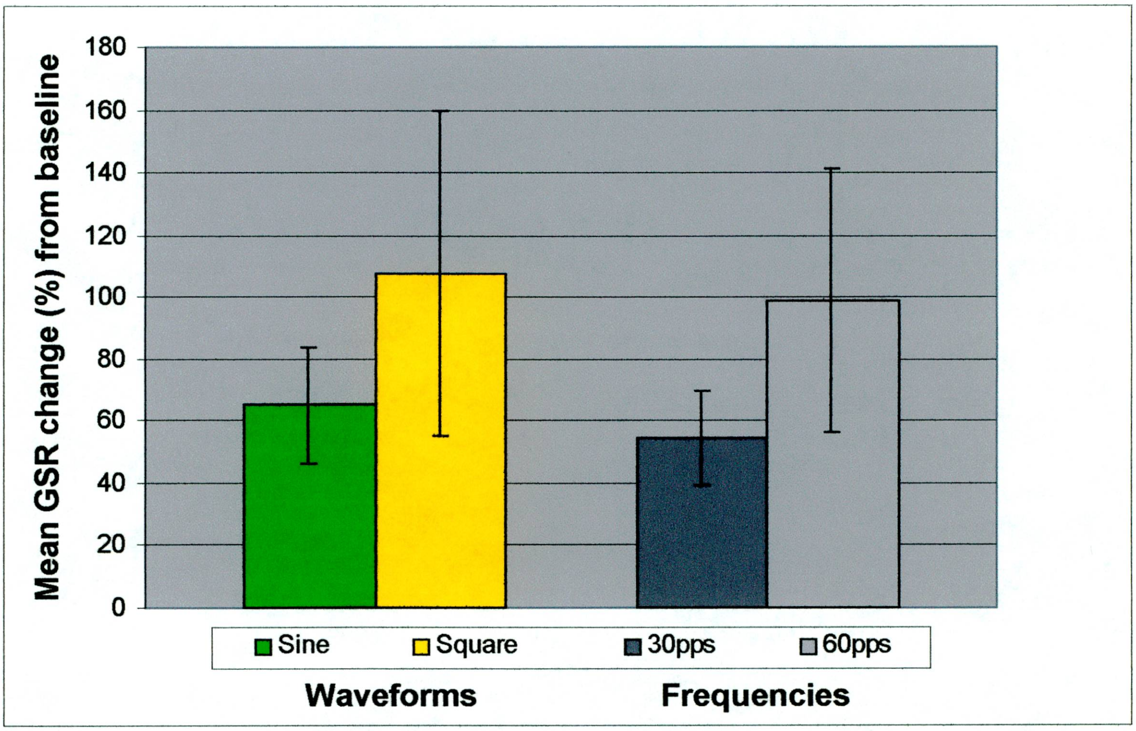

Figure 31. Mean change (%) from baseline in galvanic skin resistance (GSR) during the 10-second contractions equal to 10% MVC using a 100-μs pulse width. Error bars indicate standard error.

Mean change in galvanic skin resistance (GSR) from baseline using a 500-μs pulse width is shown in Figure 32. There were no significant differences when the Russian, sine, and square waveforms were compared (p>0.05). Changes in frequency (30- and 60-pps) did not significantly affect the change from baseline in GSR during an isometric quadriceps contraction whose electrically stimulated force was equal to 10% of the MVC (p>0.05).

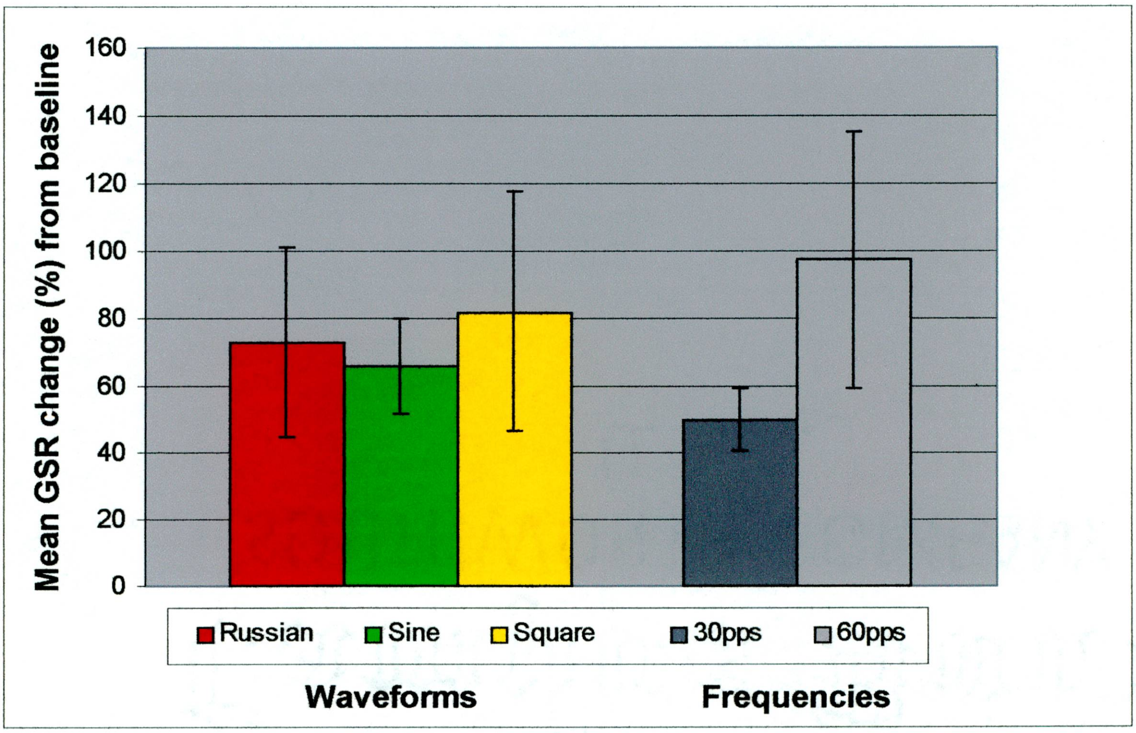

Figure 32. Mean change (%) from baseline in galvanic skin resistance (GSR) during the 10-second contractions equal to 10% MVC using a 500-μs pulse width. Error bars indicate standard error.

Appendix III.

Additional Tables

Table 2. Series 2: Mean change from baseline in stimulation current (mA) during the 4-minute contraction and 5-minute recovery period. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4
Russian	10.20 ±1.41	12.47 ±1.92	14.97 ±2.92	17.33 ±3.48	18.67 ±4.33
Interferential	38.33 ±10.73	49.33 ±1.20	49.33 ±1.20	48.67 ±1.86	49.33 ±1.20
Sine	0.25 ±0.03	0.30 ±0.03	0.36 ±0.04	0.38 ±0.03	0.39 ±0.02
Square	0.71 ±0.15	0.91 ±0.30	1.02 ±0.04	1.19 ±0.24	1.40 ±0.12

Table 3. Series 2: Mean visual analog scale (VAS) scores during the 4-minute electrically stimulated contraction. Means and standard errors are given.

Waveform	S1	S2	S3	S4
Russian	6.47 ±0.35	8.43 ±0.22	9.20 ±0.27	9.23 ±0.29
Sine	6.95 ±0.49	6.40 ±0.57	6.30 ±1.04	5.95 ±1.34
Square	6.60 ±0.75	7.10 ±1.00	8.28 ±0.36	8.20 ±0.47

Table 4. Series 2: Mean verbal response scale (VRS) scores during the 4-minute electrically stimulated contraction. Means and standard errors are given.

Waveform	S1	S2	S3	S4
Russian	7.33 ±0.33	8.67 ±0.33	9.17 ±0.17	9.17 ±0.17
Sine	7.00 ±0.71	6.50 ±0.65	6.50 ±0.96	6.25 ±1.03
Square	6.50 ±0.96	7.13 ±1.16	8.50 ±0.29	8.38 ±0.55

Table 5. Series 2: Mean change (%) from baseline in ventilation (V_E) during the 4-minute contraction and 5-minute recovery period. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	-16.85 ±20.15	15.55 ±10.45	12.00 ±40.00	31.50 ±31.50	72.50 ±14.50	22.50 ±6.50	-7.00 ±23.00	-9.46 ±13.55
Sine	37.25 ±10.59	32.25 ±7.27	59.00 ±14.68	69.25 ±14.19	52.00 ±6.48	52.68 ±22.24	9.85 ±17.06	48.13 ±38.10
Square	-6.00 ±21.10	-13.75 ±24.10	-4.25 ±9.20	21.88 ±29.50	31.50 ±29.48	21.00 ±7.15	5.25 ±12.49	42.25 ±50.32

Table 6. Series 2: Mean change (%) from baseline in oxygen consumption (VO_2) during the 4-minute contraction and 5-minute recovery period. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	-14.85 ±23.15	22.50 ±6.50	0.50 ±24.50	31.90 ±36.10	70.50 ±8.50	21.50 ±7.50	-15.40 ±19.60	-14.10 ±9.90
Sine	41.75 ±11.43	32.75 ±13.09	55.50 ±13.67	69.00 ±19.52	45.75 ±12.78	46.30 ±18.43	6.18 ±20.77	48.80 ±42.15
Square	5.00 ±30.27	-6.50 ±27.28	-1.90 ±7.46	39.00 ±33.35	39.50 ±33.87	28.50 ±8.22	5.50 ±14.26	44.00 ±50.42

Table 7. Series 2: Mean change (%) from baseline in carbon dioxide production (VO_2) during 4-minute contraction and 5-minute recovery. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	6.10 ±3.10	21.50 ±21.50	12.50 ±39.50	44.50 ±25.50	83.50 ±16.50	33.00 ±15.00	-9.50 ±23.50	-11.10 ±15.90
Sine	44.25 ±11.85	31.00 ±7.66	64.75 ±15.59	81.25 ±17.96	63.25 ±10.26	71.50 ±22.23	14.65 ±19.04	54.90 ±41.33
Square	1.50 ±29.15	-2.75 ±31.30	4.50 ±8.09	45.75 ±35.70	58.25 ±44.56	46.25 ±16.54	18.00 ±20.28	44.50 ±47.02

Table 8. Series 2: Mean change (%) from baseline in respiratory quotient (RQ) during the 4-minute contraction and 5-minute recovery. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	-1.10 ±0.00	-2.00 ±11.00	8.85 ±11.15	12.15 ±9.85	8.25 ±3.75	8.85 ±3.15	6.25 ±1.65	2.80 ±5.10
Sine	0.55 ±0.78	-1.00 ±5.91	4.93 ±4.16	7.40 ±3.29	11.23 ±3.43	-14.18 ±27.96	-19.95 ±26.16	-22.90 ±25.18
Square	-3.50 ±1.78	-0.05 ±5.03	5.98 ±1.27	3.90 ±5.09	11.40 ±5.66	12.28 ±5.38	10.03 ±4.55	0.30 ±4.11

Table 9. Series 2: Mean change (°C) from baseline in skin temperature under the electrode during the 4-minute contraction and 5-minute recovery. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	0.005 ±0.002	0.008 ±0.005	0.011 ±0.005	0.014 ±0.006	0.013 ±0.003	0.010 ±0.008	0.011 ±0.007	0.009 ±0.005
Sine	0.003 ±0.001	0.008 ±0.002	0.010 ±0.003	0.012 ±0.004	0.006 ±0.004	0.006 ±0.003	0.006 ±0.003	0.005 ±0.003
Square	0.003 ±0.001	0.005 ±0.001	0.006 ±0.003		0.005 ±0.005	0.003 ±0.002	0.003 ±0.001	0.002 ±0.001

Table 10. Series 2: Mean change (°C) from baseline in skin temperature at the forehead during the 4-minute contraction and 5-minute recovery. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	0.10 ±0.06	0.10 ±0.03	0.18 ±0.02	0.24 ±0.04	0.38 ±0.15	0.27 ±0.03	0.24 ±0.07	0.21 ±0.10
Sine	0.13 ±0.02	0.51 ±0.33	0.18 ±0.05	0.32 ±0.12	0.25 ±0.09	0.49 ±0.04	0.51 ±0.28	0.48 ±0.30
Square	0.05 ±0.02	0.09 ±0.01	0.28 ±0.10	0.05 ±0.02	0.47 ±0.18	0.63 ±0.31	0.89 ±0.48	0.81 ±0.48

Table 11. Series 2: Mean change (°C) from baseline in skin temperature at the left quadriceps muscle during the 4-minute contraction and 5-minute recovery. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	0.05 ±0.02	0.08 ±0.04	0.11 ±0.05	0.09 ±0.05	0.05 ±0.03	0.07 ±0.02	0.05 ±0.01	0.07 ±0.03
Sine	0.03 ±0.02	0.06 ±0.02	0.08 ±0.05	0.08 ±0.05	0.08 ±0.03	0.10 ±0.03	0.07 ±0.02	0.07 ±0.02
Square	0.01 ±0.01	0.03 ±0.02	0.04 ±0.01	0.02 ±0.02	0.06 ±0.03	0.08 ±0.02	0.11 ±0.06	0.11 ±0.06

Table 12. Series 2: Mean change (%) from baseline in surface blood flow at the forehead during the 4-minute contraction and 5-minute recovery. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	26.97 ±20.98	20.00 ±28.92	45.67 ±26.27	21.03 ±26.90	10.87 ±12.61	43.93 ±33.08	22.67 ±13.28	3.60 ±11.45
Sine	25.33 ±33.12	47.67 ±43.00	67.13 ±56.49	30.33 ±35.83	15.33 ±24.54	16.33 ±22.67	2.10 ±0.63	43.33 ±44.75
Square	27.67 ±68.79	74.00 ±39.55	61.67 ±31.26	12.33 ±56.78	129.33 ±55.62	93.67 ±31.47	146.67 ±78.39	99.67 ±75.34

Table 13. Series 2: Mean change (%) from baseline in diastolic blood pressure (DBP) during the 4-minute contraction and 5-minute recovery period. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	8.24 ±13.30	18.10 ±14.00	13.20 ±3.72	8.77 ±8.04	8.30 ±13.00	-1.30 ±13.20	-2.40 ±11.70	-1.60 ±17.80
Sine	6.53 ±2.31	10.58 ±0.53	11.11 ±6.42	14.29 ±4.00	14.64 ±4.28	0.88 ±5.12	6.17 ±8.10	-0.35 ±5.78
Square	3.74 ±2.26	12.21 ±3.76	14.54 ±5.00	13.58 ±5.50	19.41 ±5.55	0.51 ±2.01	0.51 ±2.01	-0.45 ±2.78

Table 14. Series 2: Mean change (%) from baseline in systolic blood pressure (SBP) during the 4-minute contraction and 5-minute recovery period. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	5.84 ±7.03	12.90 ±12.30	9.77 ±2.50	13.00 ±11.80	11.70 ±10.30	1.35 ±7.40	-0.40 ±8.42	-2.50 ±10.40
Sine	4.86 ±2.50	14.35 ±4.12	11.73 ±4.16	9.61 ±0.81	7.33 ±0.60	2.62 ±1.32	2.82 ±3.12	0.39 ±3.95
Square	-0.64 ±2.07	6.16 ±1.35	9.23 ±3.57	6.08 ±4.43	11.69 ±1.36	1.07 ±2.24	-3.27 ±3.08	-5.24 ±2.05

Table 15. Series 2: Mean change (%) from baseline in heart rate during the 4-minute contraction and 5-minute recovery. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	1.47 ±3.60	-4.50 ±1.27	4.70 ±4.90	3.33 ±7.37	-5.63 ±5.58	-8.03 ±4.43	-9.67 ±1.86	-0.10 ±6.66
Sine	-2.70 ±2.13	8.20 ±6.28	3.93 ±5.24	2.00 ±5.86	5.77 ±7.74	-1.53 ±5.65	-4.16 ±8.13	4.40 ±4.38
Square	-2.83 ±12.26	1.93 ±9.14	-1.43 ±11.84	3.67 ±15.06	-8.33 ±12.91	-5.33 ±11.78	-9.60 ±12.45	0.23 ±5.17

Table 16. Series 2: Mean change (%) from baseline in galvanic skin resistance during the 4-minute contraction and 5-minute recovery. Means and standard errors are given.

Waveform	S0	S1	S2	S3	S4	R1	R3	R5
Russian	57.93 ±60.26	118.10 ±20.43	136.53 ±49.43	98.67 ±26.38	96.77 ±38.57	26.47 ±2.13	-38.33 ±12.72	-47.33 ±25.44
Sine	62.03 ±41.53	96.33 ±46.76	94.00 ±30.29	91.70 ±35.72	85.73 ±25.33	12.35 ±19.97	-32.50 ±8.55	-53.54 ±24.86
Square	48.80 ±7.90	46.10 ±18.80	60.75 ±6.25	71.20 ±34.80	79.15 ±26.85	23.45 ±41.45	-24.65 ±48.35	-52.50 ±41.50

Appendix IV.

Forms

Subject Identification # ___________

Subject Name: _________________________ Gender: M F Age: ___________years

Height: ______ cm Weight: ______ kg Phone Number: (_____) ______-_________

Baseline Measurements:

HR: _____ bpm BP: _____/_____ mmHg MVC: Left: ______ kg Right: ______ kg

Skin temperature: Forehead: _____°C Under electrode: _____°C Left quad: _____°C

Series 1 – Day 1

Trial #	Code/File	Waveform	Frequency (pps)	Pulse width (μs)	VRS (0-10)	VAS (0-10)
	11R31	Russian	30	100		
	11R61	Russian	60	100		
	11R35	Russian	30	500		
	11R65	Russian	60	500		
	11I31	IF	30	100		
	11I61	IF	60	100		
	11S31	Sine	30	100		
	11S61	Sine	60	100		
	11S35	Sine	30	500		
	11S65	Sine	60	500		
	11P31	Square	30	100		
	11P61	Square	60	100		
	11P35	Square	30	500		
	11P65	Square	60	500		

Subject Initials – Series # - Day # - Waveform first letter – Frequency first digit – Pulse width first digit. Example: Subject John Smith's (**JS**) first series (**1**), on the first day (**1**) of the research, receiving Russian (**R**) waveform at 30 pps (**3**) with a pulse width of 100μs (**1**) would have the following code/file: **JS11R31**.

Series 2 – Days 1 & 2

Trial #	Code/File	Waveform	Frequency (pps)	Pulse width (μs)	VRS 1	VRS 2	VRS 3	VRS 4	VAS 1	VAS 2	VAS 3	VAS 4
	21R31	Russian	30	100								
	21I31	IF	30	100								
	21S31	Sine	30	100								
	21P31	Square	30	100								

Subject Identification # ___________

Subject Name: __________________________ Gender: M F Age: ___________years

Height: ______ cm Weight: ______ kg Phone Number: (_____) ______-_________

Baseline Measurements:

HR: _____ bpm BP: _____/_____ mmHg MVC: Left: ______ kg Right: ______ kg

Skin temperature: Forehead: _____°C Under electrode: _____°C Left quad: _____°C

Series 1 – Day 2

Trial #	Code/File	Waveform	Frequency (pps)	Pulse width (μs)	VRS (0-10)	VAS (0-10)
	12R31	Russian	30	100		
	12R61	Russian	60	100		
	12R35	Russian	30	500		
	12R65	Russian	60	500		
	12I31	IF	30	100		
	12I61	IF	60	100		
	12S31	Sine	30	100		
	12S61	Sine	60	100		
	12S35	Sine	30	500		
	12S65	Sine	60	500		
	12P31	Square	30	100		
	12P61	Square	60	100		
	12P35	Square	30	500		
	12P65	Square	60	500		