Effects of Neuromuscular Electrical Stimulation of Various Frequencies and Intensities on Energy Expenditure

In partial fulfillment of the requirements for the Degree
Master of Science in
Applied Sport Science and Coaching

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ABSTRACT

TITLE OF THESIS: Effects of Neuromuscular Electrical Stimulation of Various Frequencies and Intensities on Energy Expenditure.

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The purpose of this study was to determine the effects of neuromuscular electrical stimulation (NMES) of various intensities (25, 50, 75, and 100 mA) and frequencies (8, 12, 20, 50 Hz) on energy expenditure of the knee extensor muscles (KEM). Fourteen male university students between 20 and 24 years of age were submitted to 5 min of each intensity at each frequency during NMES on different days with the use of a portable stimulator (Respond II, EMPI; impulse width of 300 microseconds; duty cycle: 55s on and 2s off) and adhesive electrodes (Pals Plus™, EMPI). Oxygen uptake was measured in the supine position at rest and during NMES of both KEM. Energy expenditures (kcal . hr^{-1} . kg of KEM^{-1}) of the four frequencies of each intensity (mean : 25 mA= 1.8; 50 mA= 7.8; 75 mA= 21.6; 100 mA= 26.3) were not significantly different ($p>0.05$) and that of the different intensities of each frequency were significantly different ($p<0.05$-$p<0.001$) except in 50 Hz between 75 and 100 mA ($p>0.05$). The highest energy

expenditure (28.1 kcal . hr^{-1} . kg of KEM^{-1}) was observed at a stimulation frequency of 8 Hz ($p>0.05$) at an intensity of 100 mA.

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I would like to express my sincere thanks to Dr. Thomas M.K. Song for his direction and guidance over my undergraduate and graduate studies. From him I have learned many lifelong skills and he has always been a source of inspiration. I would like to thank Dr. Ian Newhouse and Dr. Norm Lavoie for serving on my thesis committee. As well, I would like to express my gratitude to the participants of this study. I would like to dedicate this paper to my mother and father who have always encouraged me to pursue studies in the areas which interested me. For this I am most thankful.

Without the support of these above mentioned individuals, the completion of this study would not have been possible.

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Chapter 1

INTRODUCTION

Purpose

The purpose of this study was to quantify the oxygen uptake and energy expenditure induced by various frequencies (8, 12, 20, and 50 Hz) and intensities (25, 50, 75, 100 mA) of neuromuscular electrical stimulation of the human knee extensor muscles.

Significance

Neuromuscular electrical stimulation (NMES) has been in practice since the 18th century for treating paralyzed patients and restoring muscle function after injury (Hainaut & Duchateau, 1992). Neuromuscular electrical stimulation of healthy skeletal muscle directly affects the metabolic activity of stimulated muscle (Currier, 1991) and can play an important role in physical conditioning because it appears to complement voluntary training (Siff, 1990). Increases in local blood flow (Currier, Petrilli, & Threlkeld, 1986), serum enzyme levels (Song, Hodgkinson, Stoot, & Porter, 1990), oxygen uptake and energy expenditure (Néron & Simoneau, 1994; Simoneau, 1989; Song, Guthrie, Newhouse, & Newhouse, 1991) have been reported during NMES of skeletal muscle. It has also been reported that functional electrical stimulation improves cardiovascular and musculoskeletal fitness for individuals with spinal cord injury

(Arnold, Mcvey, Farrell, Deurloo, & Grasso, 1992; Faghri, Glaser, & Figoni, 1992).

The way in which NMES is capable of eliciting these physiological adaptations relies mainly on how the wave form, frequency, pulse width, intensity and current modulation are modified (Alon, 1991; Windsor, Lester, & Herring, 1993). There have been numerous studies which have examined how the manipulation of the frequency of NMES has affected muscular strength (Balogun, Onilari, Akeju, & Marzouk, 1993), blood flow (Currier et al., 1986), and force output of stimulated muscle (Binder-Macleod & Guerin, 1991). Research regarding the effects of various frequencies and intensities of NMES on oxygen uptake and energy expenditure of human skeletal muscle is limited. Both Simoneau (1989) and Song et al. (1991) have reported high oxygen uptakes per kg of knee muscle mass induced by an 8 Hz current frequency during NMES at high intensities in untrained male subjects. Presently, there are no studies which have examined the effects of various frequencies and intensities of NMES on energy expenditure. Quantifying the frequency and intensity of NMES which yields the greatest oxygen consumption and energy expenditure is of great importance to individuals interested in establishing NMES training programs for able bodied and physically challenged individuals.

Limitations

1. The assumption that subjects faithfully followed instructions and cooperated in all aspects of the study.
2. The assumption that the subjects were at complete rest when the initial baseline values for oxygen consumption were obtained.
3. The assumption that all subjects were fully hydrated during the testing sessions.
4. The assumption that the electrodes were accurately placed over the femoral nerve and the motor end point of the vastus lateralis.
5. The assumption that all subjects had similar muscle fiber type profiles.
6. The muscle mass of the knee extensor muscles was estimated via anthropometric measurements and arithmetic calculations.
7. The assumption that not all of the muscle fibers of the KEM were fully activated during stimulation.
8. An alpha level of 0.05 was established as the level of significance for the statistical tests.

Delimitations

1. Only four frequencies (8, 12, 20, 50 Hz) and four intensities (25, 50, 75, 100 mA) were used for the study.
2. Electrical stimulation of the muscle was delimited to a specific pulse width

(300 micro seconds) and a specific duty cycle (55 seconds on / 2 seconds off).

3. Only healthy males between the ages of 20 to 24 participated in the study.
4. Stimulus intensities were applied in a progressive fashion (25, 50, 75, 100 mA) in each frequency (8, 12, 20 and 50 Hz).

Definitions

Biphasic/bipolar: The flow of electronic current alternating in both directions from the isoelectric point (Nelson & Currier, 1991).

Energy expenditure: The amount of energy (kilocalories) liberated by a metabolic system (McArdle, Katch, & Katch, 1991).

Kilocalorie: A unit of energy, being the amount of heat necessary to raise the temperature of a liter of water 1° C, from 14.5 to 15.5° C (McArdle et al., 1991).

Knee extensor muscles: The muscles which extend the lower leg (Tortora, 1989).

Isoelectric point: Represents the point where the electrons are flowing. This point is used as reference point when describing electron flow (Nelson & Currier, 1991).

Isometric contraction: A muscular contraction in which force is generated with no noticeable shortening of the muscle fibers (McArdle et al., 1991).

Monophasic/monopolar: The flow of electrons in one direction from the isoelectric point (Nelson & Currier, 1991).

Neuromuscular electrical stimulation (NMES): The transmission of electrical current through electrodes placed on the skin surface in order to stimulate muscular contraction (Nelson & Currier, 1991).

Oxygen uptake: The amount of oxygen that is transported and utilized by active muscle (McArdle et al., 1991).

Period: The length of time from the onset of the waveform to the onset of the next waveform. The interpulse interval is included in this time period. As the frequency increases the period decreases (Nelson & Currier, 1991).

Pulse duration: The time of current flow of one wave form. The terms pulse width and period are also used (Nelson & Currier, 1991).

Pulse width: A term used to describe the time period of stimulation depending on the type of electrotherapeutic device used (Nelson & Currier, 1991).

Stimulus frequency : The number of electrical wave forms delivered per second, measured in hertz (Hz) (Nelson & Currier, 1991).

Stimulus intensity: The vertical distance from the highest to the lowest peak of one electrical wave, measured in millamperes (mA) (Nelson & Currier, 1991).

Tetanic contraction: A continous contraction of a muscle without distinct twitching (Miller & Keane, 1987).

Twitch contraction: A contractile reponse of a skeletal muscle elicited by a single maximal volley of impulses in the neurons supplying it (Miller & Keane, 1987).

Wave form: The direction of current flow. Uni-directional currents are referred to as monophasic currents and bi-directional wave forms are also referred to as alternating currents (Nelson & Currier, 1991).

Chapter 2

REVIEW OF RELATED LITERATURE

Electrical Stimulation of Muscle

The practice of inducing a muscular contraction via electrical stimulation was first reported by Galvani in 1791 (Hainaut & Duchateau, 1992). Galvani observed that, with the introduction of two dissimilar metals to a frog's muscle, a muscular contraction occurred. Interest in the use of electrical stimulation as a method of training increased when the Russian researcher Kots reported that Russian athletes were using NMES as a training modality to enhance muscular strength (Kots, 1977).

Electrostimulation involves delivering electrical impulses to the muscles via electrode pads placed firmly on the skin (Siff, 1990). The effectiveness, comfort and excitation of the muscle depends on the stimulus parameters of NMES. They are: pulse shape, frequency, duration, intensity and modulation pattern of the electrical current (Alon, 1991; Windsor et al., 1993). In healthy muscle NMES appears to be a complement to voluntary training (Hainaut & Duchateau, 1992). However, Houston (1983) cautions that although electrical stimulation is useful, it may be abused if used by individuals unfamiliar with the physiological principals of its use.

Oxygen Uptake and Energy Expenditure

The most convenient method to measure energy expenditure in the laboratory is by the collection and analysis of respiratory gases and their conversion to the caloric equivalents of oxygen (Guyton, 1991). When energy expenditure is measured at any other time of the day under resting conditions, it is normally termed resting energy expenditure and may or may not include the increase in energy expenditure associated with an individual's food ingestion or physical activity (Poehlman, 1989).

The factor that causes by far the most dramatic effect on the metabolic rate is exercise (Bray, 1985). The ingestion of food has a stimulating effect on energy metabolism due to the energy requiring processes of digesting, absorbing and assimilating the various nutrients (Belko, Van Loan, Barbbieri, & Mayclin, 1987). The magnitude of dietary induced thermogenesis can vary between 10 and 35 percent of the ingested food energy depending on the quantity and type of food eaten (McArdle et al., 1991).

A number of researchers have examined the effects of NMES on energy expenditure. A study conducted by Simoneau (1989) investigated the oxygen uptake and energy expenditure of eight male subjects following one session of NMES of the quadriceps muscles at 8 Hz. The mean energy expenditure of both legs induced by the stimulation was 74 kcal . hour $^{-1}$.

Similarly, Song et al. (1991) measured oxygen uptake and energy expenditure of various frequencies of NMES of the human knee extensor muscles (KEM) in twelve university male subjects. The range of intensities was 60 to 100 mA. The results of the study illustrated that NMES at 8 Hz induced the highest energy expenditure (64 kcal . hour $^{-1}$) followed by 12 Hz (48 kcal . hour $^{-1}$), 20 Hz (18 kcal . hour $^{-1}$), and 4 Hz (12 kcal . hour $^{-1}$), respectively.

An animal study conducted by Hoppeler, Hudlicka and Uhlmann (1987) examined the oxygen consumption in cat gracilis muscle during various frequencies of electrical stimulation. The gracilis muscle was under contraction for 120 s and oxygen consumption was measured at the frequencies of 8, 10, 12, 15, and 18 Hz. The mean oxygen consumption of the stimulated gracilis muscle (8 Hz) was 11.6 ml . g $^{-1}$. min $^{-1}$.

Frequency of Electrical Stimulation

The effectiveness of NMES depends on the frequency of the waveforms used (Alon, 1991; Siff, 1990; Windsor et al., 1993), particularly since there is a distinct difference in the recruitment patterns and functional characteristics of slow and fast twitch muscle fibers (Trimble & Enoka, 1991).

DeVahl (1992) states that different frequencies have different functions. Frequencies between 8 Hz and 20 Hz cause twitch contractions which cause a vibrational or facilitating contraction and can be described as incomplete tetany.

Randall, Imig, and Hines (1953) observed greater blood flow with lower frequencies of 7 to 14 Hz than with the higher frequencies that produced tetanic contractions. Generally, the faster the frequency of NMES, the lower the percentage of increase in blood flow (Randall et al., 1953).

However, at higher frequencies 30 - 50 Hz the contractions become fused and tetanization occurs (Guyton, 1991). It is reported that a frequency of more than 20 Hz is required to produce a smooth tetanic contraction (Hainaut & Duchateau, 1992). However, maximum muscular contraction is produced only at higher frequencies of 60 to 100 Hz (Binder-Macleod & Guerin, 1990).

Sjoholm, Sahlin, Edstrom, and Hultman (1983), while stimulating the KEM of male subjects, demonstrated that 10 Hz produced 30 percent of quadricep femoris max force, 20 Hz produced 70 percent of quadricep femoris max force, and 50 Hz yielded 90-95% of the quadricep femoris maximum force.

<u>Oxygen Uptake and Energy Expenditure</u>

A study conducted by Simoneau (1989) investigated the oxygen uptake and energy expenditure of eight male subjects following one session of NMES of the quadriceps muscles at 8 Hz. Mean oxygen uptake was 128 and 248 ml $O_2 \cdot min^{-1}$ for the right quadricep muscle and for both quadriceps muscles, respectively. When expressed per kg of estimated muscle mass, the mean oxygen uptake was 70 $ml^{-1} \cdot kg^{-1} \cdot min^{-1}$ for both legs. The mean energy expenditure of both legs induced by the stimulation was 74 kcal . hour $^{-1}$. The author states that oxygen uptake per kg of muscle mass was relatively high. However, the author states that approximately three hours of NMES of both quadriceps would have to be used to generate an energy expenditure similar to that induced by 30 min of cycling at the intensity of about 50% of $\dot{V}O_2$ max.

Song et al. (1991) measured oxygen uptake and energy expenditure of various frequencies of NMES of the human knee extensor muscles (KEM) in twelve university male subjects. The range of intensities was 60 to 100 mA. The mean $\dot{V}O_2$ of the estimated quadriceps muscle mass at 4, 8, 12, and 20 Hz were 2.4, 12.8, 9.6, and 3.5 L . hour $^{-1}$, respectively. The results of the study illustrated that NMES at 8 Hz induced the highest energy expenditure (64 kcal . hr $^{-1}$) followed by 12 Hz (48 kcal . hr $^{-1}$), 20 Hz (18 kcal . hr $^{-1}$), and 4 Hz (12 kcal . hr $^{-1}$), respectively.

Néron and Simoneau (1994) examined the effects of NMES at 8 Hz on the oxygen uptake of the KEM in 11 subjects (2 female, 9 male). Oxygen uptake was measured during electrical stimulation of both KEM at various intensities (25, 50 75, and 100 mA). The stimulation-induced increases in $\dot{V}O_2$ of the KEM were 11, 151, 326, 399 ml . min $^{-1}$ for intensities of 25, 50, 75, and 100 mA, respectively. Expressed per kg of KEM $^{-1}$ (3.14 kg) the $\dot{V}O_2$ were 4, 50, 107 and 131 ml . min $^{-1}$. kg $^{-1}$ for the same intensities.

A study conducted by Boulay, Thériault, Barbeau, Giroux, Boulay, Prud'Homme, and Simoneau (1992) compared the maximal oxygen uptake and stimulation-induced oxygen consumption of the knee extensor muscles in sedentary (N=9) and physically active (N=13) subjects. Oxygen uptake was determined at rest during 8 Hz of NMES of both knee extensor muscles, and again following a maximal ergocycle exercise test. Maximal oxygen uptake expressed per kg of fat free mass and expressed per kg of quadricep muscle mass was significantly ($p<0.05$) higher in active subjects than in sedentary subjects. The study indicated that maximal oxygen uptake per kg of quadricep muscle mass was significantly greater than that per kg of fat free mass for both sedentary (63.5 vs 45.9 ; $p<0.02$) and active (77.1 vs 65.4 $ml \cdot kg^{-1} \cdot min^{-1}$; $p<0.002$) subjects.

A recent study by Kim, Strange, Bangsbo, and Saltin (1995a) also examined the oxygen uptake of the knee extensor muscles during electrically induced muscle contractions at various exercise loads. The exercise loads were 0, 10, 20, 30, and 40 Watts (W), respectively. Electrically induced muscle contractions were performed at a frequency of 50 Hz in six male subjects. Mean peak oxygen uptake for the entire leg was 0.15 $L \cdot min^{-1}$ during no load exercise and increased to 0.71 $L \cdot min^{-1}$ at 40 W. Mean peak oxygen uptake of the quadricep muscle mass was 230 $ml \cdot min^{-1}$ at a work load of 40 W. Subjects also voluntarily performed the one-legged extension tests at the same workloads at a rate of 60 contractions . min $^{-1}$. Pulmonary oxygen uptake was the same in both exercise modes. The study suggests that electrically induced dynamic exercise is associated with cardiovascular responses similar to voluntarily performed exercise.

The metabolic response of prolonged electrically induced dynamic exercise was investigated by Kim, Bangsbo, Strange, Karpakka, and Saltin (1995b). It was demonstrated in the study that electrically induced contractions could be sustained for prolonged periods of time resulting in increased rates of oxygen consumption and energy expenditure. The subjects (N=7) performed one-legged extension exercises while in a seated position. On separate days, knee extensions were performed both voluntarily and via electrical stimulation (50 Hz) for sixty minutes at a work rate of 30 W. Pulmonary oxygen uptake in the last minute of exercise was 0.81 L . min $^{-1}$ during voluntary exercise and 1.01 L . min $^{-1}$ during the electrically induced exercise. The authors concluded that the electrically induced muscle contractions engaged the entire quadricep muscle and recruited all muscle fiber types. Thus, energy expenditure was more pronounced in the group who performed the electrically induced muscle contractions.

Hoppeler et al. (1987) conducted a study which examined the oxygen consumption in cat gracilis muscle during various frequencies of electrical stimulation. The gracilis muscle was under contraction for 120 s and oxygen consumption was measured at the frequencies of 8, 10, 12, 15, and 18 Hz. The interval between each individual bouts of stimulation was 20 minutes, by which time blood flow was reported to have returned to pre-stimulation levels. The authors reported that oxygen consumption was highest during stimulation at 8 Hz . The mean oxygen consumption of the stimulated gracilis muscle (8 Hz) was 11.6 $ml \cdot g^{-1} \cdot min^{-1}$. At the higher stimulation frequencies (10, 12, 15, and 18 Hz) oxygen consumption values remained relatively unchanged.

<u>Adenosine Triphosphate Turnover Rate</u>

The rate of adenosine triphosphate (ATP) utilization determines the rate of respiration in skeletal muscle tissue (Wilson, 1995). As a result, a number of researchers have used the turnover rate of ATP during electrical stimulation in order to determine the energy expended during NMES exercise (Bergstrom & Hultman, 1988; Hultman & Spriet, 1986; Spriet, Soderlund, Bergstrom, & Hultman, 1987).

Hultman and Sjoholm (1983) stimulated the quadricep femoris muscles of nine subjects via intramuscular electrodes for 50 s. The stimulation frequency was 20 Hz and the intensity was adjusted to produce an initial tension of 50 to 75% of the subjects maximum voluntary contraction force. The concentration of ATP was initially 5.6 mmol . kg $^{-1}$ (dry weight) and decreased during the later stages of contraction to 4.0 mmol . kg $^{-1}$ (dry weight). The authors stated that during the 50 s contraction there was a continuous breakdown of phosphocreatine (PCr) and almost the whole supply was utilized within 50 s.

Bergstrom and Hultman (1988) electrically stimulated the quadricep femoris muscles of six volunteers. Electrical stimulation (20 Hz) was used to produce contractions with a duration of 0.8 s in one leg and contractions with a duration of 3.2 s in the other leg. The same number of stimulation pulses were delivered to each leg and the total contraction time for both legs was 51 s. The mean ATP utilization rate for the leg which had a contraction duration of 0.8 s after 22 and 51 s of work was 6.6 and 4.3 mmol . kg $^{-1}$. s $^{-1}$, respectively. The ATP utilization rate of the leg which had a 3.2 s contraction duration was 5.5 and 3.9 mmol . kg $^{-1}$. s $^{-1}$ after 22 and 51 s of work, respectively. The authors concluded that contractions of shorter duration (0.8 s) caused the muscle to fatigue faster and utilized more energy than the longer contraction durations (3.2 s) because of the repeated intermittent type of work performed during the stimulation period.

Hultman and Spriet (1986) also examined the turnover rate of ATP following 45 minutes of intermittent electrical stimulation. The frequency of NMES was 20 Hz and the contraction duration was 1.6 s, separated by pauses of 1.6 s. The rate of ATP turnover was recorded at various times during the stimulation period

(80s, 15, 30, and 45 min). The ATP turnover rate was 1.86 mmol . kg $^{-1}$. s $^{-1}$ during the stimulation session. The authors concluded that after the first 80s of the NMES period, aerobic pathways provided an increasing fraction of the energy supply. This change occurred in the absence of input from the central nervous system.

A study by Spriet et al. (1987) also examined the energy release in muscle following NMES of the quadricep muscles under anaerobic conditions. Seven male subjects were stimulated (20 Hz) while leg blood flow was occluded. Sixty four contractions were delivered each lasting 1.6 s followed by 1.6 s of rest. The total contraction time was 102.4 s. The turnover rate of ATP was examined at rest and following 16, 32, 48, and 64 contractions. The ATP turnover rates during the four contraction periods were 6.12, 2.56, 2.17, and 0.64 mmol per kg of dry muscle . s $^{-1}$, respectively. The authors reported that glycolysis was responsible for 90% of the total ATP production beyond contraction 16. Glycolysis was reported to produce 195 mmol ATP per kg of dry muscle during the initial 48 contractions (76.8 s) and 15 mmol ATP . kg dry muscle $^{-1}$ during the final 16 contractions.

Sjoholm et al. (1983) examined oxidative energy metabolism in response to electrical stimulation in 15 healthy subjects. The KEM were stimulated at 30 Hz with gradually increasing voltage until 30% of maximum voluntary contraction was reached. This stimulating voltage was used for the rest of the test. A cuff that was placed around the quadriceps muscle was inflated to 240 mmHg. Stimulation at 20 Hz began 30 s later with the cuff inflated. The various stimulation times were 12, 25, 50 and 75 s, respectively. Phosphocreatine decreased during the 75 s contraction from 76 mmol per kg dry muscle down to a mean value of 9 mmol. Lactate increased during the same time period from 5 mmol per kg dry muscle to 100 mmol. There was a rapid resynthesis of PCr following the stimulation period. The authors concluded that the relationship between PCr and lactate of contracting muscle can be used as an index of glycolytic capacity. Furthermore, the authors suggest that the rate of resynthesis of PCr after contraction can be used as a non-invasive estimation of the oxidative capacity of skeletal muscle.

Blood Flow

The effects of electrical stimulation on blood flow has been examined by a number of researchers (Barclay, 1988; Currier et al., 1986; Kim et al., 1995a). It has been recognized that blood flow to skeletal muscle is correlated with the capacity of oxidative metabolism (Maxwell, Barclay, Mohrman, & Faulkner, 1977). Kim et al. (1995a) reported that peak muscle blood flow was similar at various exercise intensities (0, 10, 20, 30, and 40 W) during voluntary and electrically induced (50 Hz) dynamic exercise. The authors reported individual values for peak muscle blood flow (40 W) to be between 165-220 ml.100 g^{-1}. min^{-1}.

The majority of research in this area has been performed on animals. Aitman, Hudlicka, and Tyler (1979) examined the effects of electrically induced tetanic contractions on blood flow in rabbits. The tibialis anterior muscles of rabbits were stimulated via the peroneal nerve at supramaximal intensities either at 10 Hz continuously or with three 5 trains . min^{-1} at 40 Hz. After 30 minutes of isotonic contractions both patterns of electrical stimulation produced similar increases in blood flow. Brechue, Barclay, O'Drobinak, and Stainsby (1991) demonstrated that maximal blood flow and oxygen uptake relies mainly in the peak blood flow through the muscle rather than the oxygen uptake capacity of the muscle during electrically stimulated contractions. Two forms of isotonic contraction, tetanic and twitch, were delivered to dog gastrocnemius-plantaris muscle. The tetanic contractions were induced with a frequency of 50 Hz once per second and the twitch contractions were delivered at the same frequency but were delivered four times per second. Peak blood flow was 37% greater and decreased at a slower rate during tetanic than twitch contractions. The authors concluded that the main difference in blood flow between the two forms of contraction were due to the mechanical hindrance of blood flow. The authors suggest that there was more time for unhindered blood flow in the tetanic contractions.

Saltin (1985) investigated the blood flow and oxygen uptake per kg of the KEM during dynamic work performed at a rate of 60 contractions per minute at various workloads (0 to 60 watts). Pulmonary oxygen uptake increased linearly with the work intensity. Heart rate also increased linearly with the increased workload to a peak value of 144 beats per minute. Blood flow was also measured in the femoral vein and was 0.15 to 0.40 liters per min at rest and increased linearly during the exercise protocol. Mean maximal blood flow reached 6 liters per minute at a workload of 60 watts. Oxygen uptake of the KEM during rest was between 6 and 12 ml . min $^{-1}$ and increased linearly with the increased workloads.

Intensity of Electrical Stimulation

An exhaustive review of literature has revealed only one study which has examined the effects of various intensities on oxygen consumption. It is, however, generally accepted that metabolic processes of the body increase in direct relation to the intensity of the electrical stimulus (Currier, 1991).

Néron and Simoneau (1994) examined the effects of various intensities of NMES on the oxygen uptake of the KEM (3.14 kg) in 11 subjects (2 female, 9 male) using a stimulation frequency of 8 Hz. The oxygen uptake of both the KEM were 11, 151, 326, 399 ml . min $^{-1}$ for the intensities of 25, 50, 75, and 100 mA, respectively. Expressed per kg of KEM $^{-1}$ the values at each intensity were 4, 50, 107, and 131 ml . min $^{-1}$. kg $^{-1}$.

The majority of studies related to human metabolism report stimulus intensities as a percentage of an individual's maximal voluntary contraction (Currier et al., 1986; Spriet et al., 1987) or the subjects are required to sustain as high an intensity as possible. The lack of information regarding the effects of stimulus intensity on oxygen consumption and energy expenditure warrants further investigation.

Chapter 3

METHODOLOGY

Subjects

Fourteen healthy male university students participated in the study (see Table 1). The basic premise of the study and the risks associated with the study were explained to the subjects. Subjects gave written consent to participate in the study (see Appendix A) which was approved by the Medical Ethics Committee of Lakehead University.

Testing Schedule

Each subject underwent four sessions of electrical stimulation and one session of anthropometric measurements over two consecutive weekends. The subjects were tested at the same time of the day for each of the testing sessions.

Testing Procedure

Subjects reported to the Human Performance Laboratory in the C.J. Sanders Fieldhouse wearing shorts and a shirt. The subjects were instructed to avoid strenuous activity for at least 24 hours prior to the testing sessions and the subjects were advised not to eat anything for two hours prior to the testing.

Table 1. Characteristics of subjects

Subject	Age (yrs)	Weight (kg)	Height (cm)
1	22	67.1	178.1
2	23	99.4	180.5
3	27	85.0	175.3
4	21	77.4	183.1
5	24	80.9	182.0
6	22	77.2	176.0
7	21	84.8	177.6
8	21	66.9	180.8
9	23	91.6	180.0
10	22	106.1	176.6
11	23	101.4	182.5
12	21	80.4	189.2
13	21	87.3	188.2
14	22	68.7	173.0
Mean	22.4	83.9	180.2
S.D.	1.7	12.4	4.6

Anthropometric Measures

Weight, height, skinfolds, and girths of the thigh were measured following the procedures of the International Biological Program (Lohman, Roche, Martorell, 1988). The cross-sectional area of the thigh muscle and thigh volume (muscle plus bone) was determined from anthropometric measurement as described by Jones and Pearson (1969). The equation by Saltin (1985) was used to calculate the total mass of the knee extensor muscles (see Appendix B).

Neuromuscular Electrical Stimulation

A portable battery-powered stimulator (Respond II, EMPI) which produces a rectangular, asymmetrical-balanced biphasic pulse shape was used. Each of the four intensities (25, 50, 75, and 100 mA) were applied progressively for five minutes in each session of the four frequencies (8, 12, 20, and 50 Hz) during NMES. The electrical stimulations were delivered transcutaneously to the extensor muscles (impulse width of 300 microseconds and a duty cycle of 55 seconds on and 2 seconds off). Two 7.6 cm diameter round adhesive bipolar electrodes (PALS PLUS ™, EMPI) were placed over the proximal part of the knee extensor muscles (KEM) and over the motor point located on the vastus lateralis approximately 10 cm proximal to the upper border of the patella on each leg. The origin of the vastus lateralis muscle was determined by palpation of the contracted muscle.

One week test-retest correlations between oxygen consumption and NMES protocol (four intensities of 8 Hz) ranged from 0.89 to 0.94.

Energy Expenditure

Oxygen uptake was measured by SensorMedics MMC Horizon System in the supine position at rest (after 10 min rest) and during the NMES of both KEM. Oxygen uptake per min and per kg of thigh muscle mass and energy expenditure for the two knee extensor muscles was presented in kcal . hour $^{-1}$. kg of KEM $^{-1}$. The energy expenditure of the knee extensors was calculated using the oxygen uptake differences between resting and NMES and was calculated by one litre of oxygen multiplied by 4.9 kcal.

Data Analysis

Descriptive statistics (mean and standard deviation) were computed. The effect of each test was assessed with a repeated-measures two way ANOVA and the Tukey test was used to identify specific mean differences when a significant F ratio was observed. The level of significance was set at 0.05.

Chapter 4

RESULTS

The results of the anthropometrical characteristics of subjects are shown in Table 2. The height and weight of the subjects were in the 60 and 80 percentile of Canadian norms, respectively (Canadian Standardized Test of Fitness, 1986). The estimated knee extensor muscle mass of both legs was 4.04 kg.

The oxygen uptake values for the four different frequencies and intensities of NMES are shown in Table 3. Significant differences were found between intensities ($F=586.0$, $p<0.001$; Tukey value = 12.2, $p<0.05$) and the F ratio for the frequency and the interaction between intensity and frequency were not significant. The results from the present study demonstrate that the higher the intensity, the greater the oxygen uptake ($p<0.05$ - $p<0.001$) was found in all frequencies except in 50 Hz between 75 and 100 mA ($p>0.05$). The oxygen uptake at 100 mA of 8 Hz was the highest (95.7 ml . min $^{-1}$. kg of KEM $^{-1}$; $p>0.05$). The average oxygen uptake for the various frequencies of the intensities of 25, 50, 75, and 100 mA were 6.1, 26.5, 73.3, and 89.5 ml · min $^{-1}$ · kg of KEM $^{-1}$, respectively. There were no significant differences among frequencies in the same intensity.

The energy expenditures of various frequencies and intensities of NMES are shown in Table 4. The F ratio was similar to that of oxygen uptake and the Tukey value was 3.63 ($p<0.05$). The average energy expenditures of 25, 50, 75, and 100 mA of four frequencies were 1.79, 7.78, 21.55, 26.30, kcal . hr^{-1} . kg of KEM^{-1}, respectively.

Table 2. Anthropometrical characteristics of subjects

	Age (yr)	Weight (kg)	Height (cm)	Sum of Skinfolds* (mm)	Muscle Mass** (kg)
Mean	22.4	83.9	180.2	38.6	4.04
S.D.	1.7	12.4	4.6	12.6	0.38

S.D.: Standard deviation.

* : Sum of the skinfolds of the gluteal furrow, the third of the subischial height, and the minimum circumference above the knee.

** : Knee extensor muscles of both legs.

Table 3. Oxygen uptake of various intensities and frequencies of neuromuscular electrical stimulation.

	Frequency			
Intensity	8 Hz	12 Hz	20 Hz	50 Hz
25 mA	6.2 ± 5.2	5.6 ± 4.3	6.7 ± 4.2	5.9 ± 3.3
50 mA	25.8 ± 10.3	21.0 ± 8.3	26.7 ± 7.2	32.3 ± 15.8
75 mA	78.5 ± 13.2	68.4 ± 12.5	70.8 ± 14.5	75.5 ± 11.3
100 mA	95.7 ± 24.2	87.8 ± 23.7	90.7 ± 21.4	83.9 ± 19.5

Values are means ± SD. Units: $ml \cdot min^{-1} \cdot kg$ of KEM $^{-1}$.
Hz: Hertz. mA: Milliampre.
Frequency: No significant difference among frequencies in each intensity.
Intensity: 100 mA > 25, 50, and 75 mA ($p<0.05$-$p<0.001$) ; 75 mA > 25, and 50 mA ($p<0.05$-$p<0.001$) ; and 50 mA > 25 mA ($p<0.05$) in each frequency except 100 mA > 75 mA ($p>0.05$) in 50 Hz.

Table 4. Energy expenditures of various intensities and frequencies of neuromuscular electrical stimulation.

	Frequency			
Intensity	8 Hz	12 Hz	20 Hz	50 Hz
25 mA	1.82 ± 1.53	1.65 ± 1.26	1.97 ± 1.23	1.73 ± 0.97
50 mA	7.59 ± 3.03	6.17 ± 2.44	7.85 ± 2.12	9.50 ± 4.65
75 mA	23.08 ± 3.88	20.11 ± 3.68	20.82 ± 4.26	22.20 ± 3.32
100 mA	28.14 ± 7.11	25.73 ± 6.97	26.67 ± 6.29	24.67 ± 5.73

Values are means ± SD. Units: kcal . hr^{-1} . kg of KEM^{-1}.
Hz: Hertz. mA: Milliampre.
Frequency: No significant difference among frequencies in each intensity.
Intensity: 100 mA > 25, 50, and 75 mA ($p<0.05$-$p<0.001$) ; 75 mA > 25, and 50 mA ($p<0.05$-$p<0.001$) ; and 50 mA > 25 mA ($p<0.05$) in each frequency except 100 mA > 75 mA ($p>0.05$) in 50 Hz.

Chapter 5

DISCUSSION

The purpose of this study was to quantify the oxygen uptake and energy expenditure induced by various frequencies and intensities of NMES of the human KEM. As of today, little research has been conducted on this subject. In the present study it was demonstrated that the higher the intensity the greater the oxygen uptake and energy expenditure. Furthermore, similar energy expenditures were observed for the four various frequencies in each of the four intensities of stimulation. However, the energy expenditure of 100 mA at 50 Hz in the present study was lower ($p>0.05$) than that of the other three frequencies at the maximal intensity. Furthermore, no significant difference ($p>0.05$) in energy expenditure was observed between 75 and 100 mA in 50 Hz which indicates that fatigue may have occurred during the 50 Hz stimulation.

Intensity of Electrical Stimulation

It is known that oxygen uptake increases in an almost linear manner with work load (Saltin, 1985), and the maximal rate of oxygen consumption of muscle is limited by the supply of oxidizable substrates, the supply of oxygen , and the respiratory enzyme capacity (Wilson, 1995). The tension of muscular contraction is directly related to the intensity of the stimulation (Ferguson, Blackley, Knight, & Sultive, 1989; Garnhammer, 1983; Houston, 1983; Underwood, Kremser, Finstuen, & Greathouse, 1990) and accordingly, the oxygen uptake increases as the increment of intensity during NMES.

Duchateau (1991) reported that during the stimulation of the KEM the degree of force increase is mainly related to the intensity of stimulation that is accepted by the subject. Duchateau (1991) further states that the higher the intensity of stimulation the greater the number of muscle fibres that will be recruited. The present study did not measure force output however, it could be postulated the production of force to be closer to the maximum at high intensities

Increasing the force output in specific muscles can be done by increasing the number of motor units recruited and/or by increasing their firing frequency (Deluka, 1985; McArdle et al., 1991). In the present study, there were no significant differences between the different frequencies in each of the four intensities and it has been demonstrated that electrically induced muscle contractions are capable of recruiting all muscle fibres (Kim et al., 1995b). Therefore, it can be postulated that the change in oxygen uptake and energy expenditure is a result of the number of motor units which were recruited.

During NMES fast twitch muscle fibres are recruited before the highly oxidative slow twitch muscle fibres because they have large motor nerves and their decreased threshold for excitation (DeVahl, 1992; Solomonow,1984; Trimble & Enoka, 1990). Only at higher intensities would the small, slow twitch fatigue resistant motor units be activated (DeVahl, 1992). As a result, only at higher stimulation intensities would all muscle fibres be active resulting in greater energy expenditure and oxygen uptake.

In the present study, there were no significant changes ($p>0.05$) in energy expenditure between the muscles resting state and 25 mA of electrical stimulation at each of the four frequencies. A possible explanation for the similarity between the resting oxygen consumption and the oxygen consumption at 25 mA may be due to the small number of motor units involved.

The results of the present study illustrate that oxygen uptake and energy expenditure increased as a result of increased stimulus intensity in each frequency ($p<0.05$-$p<0.001$). The mean peak oxygen uptake and energy expenditure of the KEM was 361.6 ml . min $^{-1}$ and 106.3 kcal . hour $^{-1}$. Although the muscular activity in the present study was limited to the KEM, the energy expenditure for one hour of NMES using 100 mA at 8 Hz (95.7 $\pm$ 24.2 ml . kg . min of KEM $^{-1}$) will be similar to about 10 minutes of bicycle ergometer riding at an intensity of approximately 70 % of the $\dot{V}0_2$ max for the male university students in the present study.

Néron and Simoneau (1994) examined the effects of various intensities of NMES on the oxygen uptake of the KEM (3.14 kg) in 11 subjects (2 female, 9 male) using a constant stimulation frequency of 8 Hz. The oxygen uptake for the intensities of 25, 50, 75, and 100 mA were 4, 50, 107 and 131 ml . min $^{-1}$. kg $^{-1}$ of KEM $^{-1}$ and were greater than that of the present study at the same intensities. The higher values for oxygen consumption per kg of KEM $^{-1}$ may be due to the fact that the KEM mass was only 3.14 kg compared to the 4.04 kg KEM mass in the present study. Thus, the metabolic demands placed per kg of KEM would be greater in Néron and Simoneau's (1994) experiment. Similarly, when oxygen uptake was expressed for both KEM, the results of Néron and Simoneau (1994) were slightly greater than that in the present study. The higher values may be due to the constant electrical stimulus that was used in comparison with the present study which used a duty cycle of 55 s on 2 s off. It is also possible that the fitness level of the subjects who participated in the present study may not have been as high as the subjects who participated in Néron and Simoneau's (1994) study. Thus, leading to lower values for oxygen uptake. In the present study, it is also possible that not all of the muscle fibers of the KEM were fully activated during stimulation.

Simoneau (1989) indicated that the mean oxygen uptake was 70 ml . kg $^{-1}$. min $^{-1}$ and the mean energy expenditure of both legs induced by the stimulation was 74 kcal . hour $^{-1}$. This would be similar to 30 min of cycle ergometer riding at an intensity of about 50% of $\dot{V}O_2$ max. The energy expenditure is lower than that of the present study. A possible reason for the difference may be due to the fact that not all of the subjects in Simoneau's study were stimulated at 100 mA. This explanation supports the hypothesis that the higher the intensity of stimulation the greater the oxygen uptake and energy expenditure.

The oxygen uptake values reported by Song et al. (1991) were lower than that of the present study and it may be due to the range of intensities which were used (60 - 100 mA). This study supports the results of the present study in which the greater the intensity of stimulation the greater the oxygen uptake and energy expenditure.

Boulay et al. (1992) also reported a lower mean oxygen uptake value when compared to the present study. This study did not indicate stimulus intensity. The subjects in Boulay et al. (1992) may not have been stimulated at maximal intensities. Thus, leading to the lower values for oxygen uptake when compared to the present study.

A recent study by Kim et al. (1995a) demonstrated similar values for oxygen uptake of the KEM when compared to the present study. Oxygen uptake of the knee extensor muscles during electrical induced muscle contractions (50 Hz) were measured at various exercise loads while subjects performed a cycle ergometer task. The exercise loads were 0, 10, 20, 30, and 40 Watts (W), respectively. When expressed per kg of KEM mass the oxygen uptake was 92 $ml \cdot kg^{-1} \cdot min^{-1}$.

In the present study the greatest oxygen uptake per kg of KEM mass was induced by an intensity of 100 mA at 8 Hz (95.7 ml . kg^{-1} . min^{-1} ; $p>0.05$). Therefore, it could be presumed that the metabolic demand placed on the KEM during dynamic knee extension at 40 W would be similar to that of the NMES of the KEM at an intensity of 100 mA at 8 Hz in the present study.

Frequency of Electrical Stimulation

In the present study no significant differences ($p>0.05$) were found in oxygen uptake and energy expenditure for the four various frequencies in each of the four intensities of stimulation. These findings possibly suggest that the rate of energy expenditure is dependent on the intensity but not the frequency. However, the greatest energy expenditure in the present study was induced at a stimulation frequency of 8 Hz ($p>0.05$) at an intensity of 100 mA.

Song et al. (1991) observed that 8 Hz induced the highest energy expenditure ($p>0.05$) during the NMES of the KEM at various frequencies. The result for peak energy expenditure is lower than the results obtained in the present study at the same stimulation frequency. This may be a result of the lower intensities which were used in their experiment. These findings possibly suggest that the rate of energy expenditure is dependent on the intensity but not the frequency. Simoneau (1989) also demonstrated high oxygen consumption and energy expenditure values at a stimulation frequency of 8 Hz in eight male subjects following one session of NMES of the quadriceps muscles.

Similar findings were demonstrated in an animal study (Hoppler et al., 1987). Hoppler et al. (1987) reported that oxygen consumption was the greatest at 8 Hz and that there was a sharp drop in oxygen uptake at frequencies lower than 8 Hz while stimulating cat gracilis muscle. Further support for the present study in relation to lower frequency stimulation producing a greater energy expenditure was demonstrated by Loiselle and Wallsley (1982). The authors observed that the energy cost of tension development was reported to be 4 times as great when the tension was developed with unfused twitches instead of fully fused tetanus achieved by asynchronous activation of motor units. The authors also indicated that the energy cost of tension development was greater with unfused twitches instead of fully fused tetanus due to the lower rate of cross bridge formation during the plateau phase of a tetanus when compared to that of the twitch contractions.

The change in blood flow due to NMES has not been done in the present study. However, the change of blood flow has been discussed due to the close relationship between blood flow and energy expenditure.

The effect of NMES on blood flow has been examined (Barclay, 1988; Currier et al., 1986; Kim et al., 1995a) and it has been recognized that blood flow to skeletal muscle is correlated with the capacity of oxidative metabolism (Maxwell et al., 1977; Wilson, 1995). Furthermore, Brechue et al. (1991) demonstrated that maximal blood flow and oxygen uptake relies mainly in the peak blood flow through the muscle rather than the oxygen uptake capacity of the muscle during electrically stimulated contractions.

Kim et al. (1995a) reported that the peak muscle blood flow was similar at various exercise intensities during voluntary (10, 20, 30, and 40 W) and electrically induced dynamic knee extension exercise (50 Hz). It could be presumed that the frequency required to activate the KEM would vary according to the force the KEM exerted (Sjoholm et al., 1983). Thus, the similar peak blood flow values between the two forms of exercise suggest that the local metabolism may be dependent on the intensity not on the frequency.

Randall et al. (1953) found greater blood flow with lower frequencies of 7 to 14 Hz than with the higher frequencies that produced tetanic contractions. Generally, the faster the frequency of NMES, the lower the percentage of increase in blood flow (Randall et al., 1953). The results of Randell et al. (1953) support the highest energy expenditure of the 8 Hz ($p>0.05$) at the intensity of 100 mA in the present study. Further support of the highest energy expenditure at 8 Hz was demonstrated by Zicot and Rigaux (1995). The authors reported that NMES of the leg muscles at 9 Hz (31 mA) increased femoral blood flow by 276% when compared to the blood flow at rest.

Perhaps the reason why 8 Hz at an intensity of 100 mA yielded the greatest energy expenditure ($p>0.05$) in the present study may be due to the fact that this stimulation frequency produces a more rhythmical or facilitating contraction to occur in the muscle. DeVahl (1992) states that different frequencies have different functions. Frequencies between 8 Hz and 20 Hz cause twitch contractions which cause a vibrational or facilitating contraction and can be described as incomplete tetany.

The decrease of energy expenditure ($p>0.05$) of 50 Hz at the intensity of 100 mA in the present study may be due to fatique. It could be assumed that there would have been a decrease in ATP resythesis and an increase in the metabolites associated with the hydrolysis of ATP, thus, a decrease in energy expenditure (Hultman & Sjoholm, 1983). High frequency fatigue could only occur due to the impairment of neuromuscular transmission or failure of membrane excitation (Edwards, 1984; Sjoholm et al., 1983).

Currier et al. (1986) reported that stimulating skeletal muscle at 50 Hz did not cause a significant increase in blood flow ($p>0.05$) when the stimulus intensity increased from 10 % to 30 % of MVC. It has been demonstrated that blood flow to skeletal muscle is correlated with the capacity of oxidative metabolism

(Maxwell et al., 1977; Wilson, 1995). Therefore, the results of Currier et al. (1986) support the findings of the present study. A possible reason why blood flow did not increase significantly in Currier et al. (1986) may be due to the fused tetanic contractions which are produced at a frequency of 50 Hz (Guyton, 1991). Although blood flow was not measured in the presented study, it could be postulated that the blood flow to the KEM muscles may have been mechanically occluded as a result of the 50 Hz stimulation at 100 mA. Thus, leading to lower energy expenditure values.

Sjoholm et al. (1983) observed that when the KEM underwent stimulation frequencies of 10, 20, 30, 40, and 50 Hz, the greatest increase in tension occurred in the frequency range of 10 to 20 Hz. Tension increased gradually as the frequency of stimulation was further increased. This study supports the findings of the present study in which no significant differences in energy expenditure ($p>0.05$) between 20 and 50 Hz at an intensity of 100 mA were observed.

CHAPTER 6

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

The purpose of this study was to determine the effects of neuromuscular electrical stimulation (NMES) of various intensities (25, 50, 75, and 100 mA) and frequencies (8, 12, 20, 50 Hz) on energy expenditure of the KEM. Fourteen male university students underwent 5 min of each intensity of each frequency during NMES of both KEM on different days with the use of a portable stimulator (Respond II, EMPI; impulse width of 300 microseconds; duty cycle: 55s on and 2s off) and adhesive electrodes (Pals Plus™, EMPI). Oxygen uptake was measured in the supine position at rest and during NMES. The results demonstrate the higher the intensity, the greater the oxygen uptake and energy expenditure ($p<0.05$ - $p<0.001$) in all frequencies except in 50 Hz between 75 and 100 mA ($p>0.05$). The average oxygen uptake for the various frequencies of the intensities of 25, 50, 75, and 100 mA were 6.1, 26.5, 73.3, and 89.5 ml · min $^{-1}$ · kg of KEM $^{-1}$, respectively. Similarly, the average energy expenditures of the four frequencies at the various intensities were 1.79, 7.78, 21.55 and 26.30 kcal . hr $^{-1}$. kg of KEM $^{-1}$. There were no significant differences among the frequencies in the same intensity for either oxygen uptake or energy expenditure. The highest oxygen uptake (95.7 ml . min $^{-1}$. kg of KEM $^{-1}$) and energy expenditure (28.1 kcal

. hr^{-1} . kg of KEM $^{-1}$) was induced at a stimulation frequency of 8 Hz ($p>0.05$) at an intensity of 100 mA.

Conclusions

The results of this study indicated that higher stimulation intensities induce greater oxygen uptakes and energy expenditures. As well, the stimulation frequencies in each intensity yielded similar values for oxygen uptake and energy expenditure. However, the greatest energy expenditure was observed at a stimulation frequency of 8 Hz ($p>0.05$) at an intensity of 100 mA.

Recommendations

The application of NMES training programs has tremendous potential for improving the function of patients with musculoskeletal conditions, as well as for enhancing athletic performance. Future studies should examine the physiological effects of long term NMES training programs on athletes as well as individuals who are unable to produce voluntary muscle contractions.

Future studies examining the effects of NMES on energy expenditure should use an intensity of 100 mA and a frequency of 8 Hz due to the fact that these stimulation parameters induced the greatest energy expenditure ($p>0.05$) in the present study. Further studies should examine the optimal number of hours that NMES should be applied for an effective training session. More specifically, to verify whether a greater number of hours per day (i.e., 6, 5, 4, 3 hrs) of NMES would lead to a significant differences between the various hours of stimulation. Such information would be useful for designing NMES training programs for individuals who are unable to voluntarily contract the KEM.

Further studies should investigate the effects of NMES on muscular endurance of the KEM using an intensity of 100 mA and a frequency of 8 Hz. It is already known that the aerobic-oxidative potential of the KEM can be improved via NMES (Gauthier et al., 1992). However, both the optimal number of hours per day and the number of weeks using the above mentioned stimulus parameters should be examined. Thériault, Thériault, and Simoneau (1994) illustrated that there were significant differences in the total work output (TWO), and the metabolic profile of the KEM following 4 weeks of NMES at 8 Hz for 8 h . day $^{-1}$. However, 4 additional weeks did not significantly alter the metabolic profile of the KEM nor did it alter the TWO of the KEM. Similarly, Gauthier et al. (1992) reported that stimulation of the KEM at 8 Hz for 8 hrs . day $^{-1}$ appeared to produce no further metabolic changes in the KEM when compared to 3 hrs . day $^{-1}$. Thus, studies verifying the optimal number of weeks of training and hours each session should be further investigated.

Another study related with the present study which should be examined is the effects of NMES training programs on muscular strength. The results of the present study demonstrated that 100 mA induced the greatest energy expenditure and that these stimulation parameters lead to fatiguing conditions in the KEM. It would be of great value to establish the optimal number of training sessions per week and the number of weeks of training needed to increase the strength of the KEM. More specifically, to verify whether or not a greater number of training sessions per week (i.e., 3 vs 4) and number of weeks of training (4 vs 6) of NMES can lead to increases in KEM strength. The results of such studies further advance the knowledge of individuals interested in establishing NMES training programs for able bodied and physically challenged individuals.

REFERENCES

Aitman, T.J., Hudlicka, O., & Tyler, K.R. (1979). Long-term effects of tetanic stimulation on blood flow, metabolism and performance of fast skeletal muscle. Journal of Physiology, 28, 36P.

Almekinders, L.C. (1984). Transcutaneous muscle stimulation for rehabilitation. The Physician and Sports Medicine, 12, 118-124.

Alon G. (1991). Principles of electrical stimulation. In Nelson, R.M. & Currier, D.P. (Eds.) Clinical Electrotherapy, (2nd Ed.) pp. 35-105. Connecticut: Appleton & Lange Publishers.

Arnold, P.B., Mcvey, P.P., Farrell, W.J., Duerloo, T.M., & Grasso, A.R. (1992). Functional electrical stimulation: Its efficacy and safety in improving pulmonary function and Muscoskeletal fitness. Archives of Physical Medicine and Rehabilitation, 73, 665-668.

Asmussen, E., Johansen, S.H., Jorensen, M., & Nielsen, M. (1965). On the nerve root factors controlling respiration and circulation during exercise: experiments with curarization. Acta Physiologica Scandinavia, 63. 343-350.

Balogun, J.A., Onilari, O.O., Akeju, O.A., & Marzouk, D.K. (1993). High voltage electrical stimulation in the augmentation of muscle strength: Effects of pulse frequency. Archives of Physical Medicine and Rehabilitation, 74, 910-916.

Barclay, J.K. (1988). Physiological determinants of Q_{max} in contracting canine skeletal muscle in situ. Medicine and Science in Sports and Exercise, 20, S113-S118.

Belko, A.Z., Vanloan, M., Barhieri, T.F., & Mayclin, P. (1987). Diet, exercise, weightlifting, and energy expenditure in moderately overweight women. International journal of Obesity, 11, 93-104.

Bergstrom, M. & Hultman, E. (1988). Energy cost and fatigue during intermittent electrical stimulation of human skeletal muscle. Journal of Applied Physiology, 65, 1500-1505.

Binder-Macleod, S.A., & Guerin, T. (1990). Preservation of force output through progressive reduction of stimulation frequency in human quadriceps femoris muscle. Physical Therapy, 70, 619-635.

Boulay, P., Thériault, R., Barbeau, P., Giroux, M., Boulay, M.R., Prud'Homme, D., & Simoneau, J.A. (1992). Difference between VO_2 max and peripheral muscle oxygen consumption in sedentary and physically active human human subjects. Medicine and Science in Sports and Exercise, 23, S145.

Bray, G.A. (1985). Regulation of energy balance. Physiologist, 28, 186-192.

Brechue, W.F., Barclay, J.K., O'Drobinak, D.M., & Stainsby, W.N. (1991). Differences between VO_2 maxima of twitch and tetanic contractions are related to blood flow. Journal of Applied Physiology, 71, 131-135.

Canadian Standardized Test of Fitness: Operational manual. (1986). The Minister of State, Fitness and Amateur Sport. Government of Canada.

Currier, D.P., Petrilli, C.R., & Threlkeld, A.J. (1986). Effect of graded electrical stimulation on blood flow to healthy muscle. Physical Therapy, 66, 937-943.

Currier, D.P. (1991). Neuromuscular stimulation for improving muscular strength and blood flow, and influencing changes. In Nelson, R.M., & Currier, D.P. (Eds.) Clinical Electrotherapy, (2nd Ed.) Connecticut: Appleton & Lange Publishers. pp. 105-169.

Deluca, C.J. (1985). Control properties of motor units. Journal of Experimental Biology, 115, 125-136.

DeVahl, J. (1992). Neuromuscular electrical stimulation (NMES) in rehabilitation. In Gersh, M.R. (Ed) Electrotherapy in Rehabilitation, Philadelphia: F.A. Davis Company. pp. 218-268.

Duchateau, J. (1991). Electrostimulation: mise au point. Sport, 133, 34-37.

Edwards, R.H.T. (1984). New techniques for studying human muscle function, metabolism, and fatique. Muscle and Nerve, 7, 599-609.

Faghri, P.D., Glaser, R.M., & Figoni, S.F. (1992). Functional electrical stimulation leg cycle ergometer exercise: Training effects on cardiorespiratory responses of spinal cord injured subjects at rest and during submaximal exercise. Archives of Physical Medicine and Rehabilitation, 73, 1085-1093.

Ferguson, J.P., Blackley, M.W., Knight, R.D. & Sutlive, T.G. (1989). Effects of varying electrode site placements on the torque output of an electrically stimulated involuntary quadricep femoris muscle contraction. Journal of Orthopedic Sports Physical Therapy, 11, 24-29.

Garnhammer, J. (1983). An introduction to the use of electrical stimulation with athletes. National Strength and Conditioning Journal, 5, 44-45.

Gauthier, J.M., Thériault, R., Thériault, G., Gelinas, Y., & Simoneau, J.A. (1992). Electrical stimulation-induceed changes in skeletal muscle enzymes of men and women. Medicine and Science in Sports and Exercise, 24, 1252-1256.

Guyton, A.C. (1991). Textbook of Medical Physiology Philadelphia: W.B. Saunders Company. pp. 793-795.

Hainaut, K. & Duchateau, J. (1992). Neuromuscular electrical stimulation and voluntary exercise. Sports Medicine, 14, 100-113.

Hoppeler, H., Hudlicka, O., & Uhlmann (1987). Relationship between mitochondria and oxygen consumption in isolated cat muscles. Journal of Physiology, 385, 661-675.

Houston, M.E. (1983). Effects of electrical stimulation on skeletal muscle of injured and healthy athletes. Canadian Journal of Applied Sport Sciences, 8, 48-51.

Hultman, E. & Sjoholm, H. (1983). Energy metabolism and contraction force of human skeletal muscle in situ during electrical stimulation. Journal of Physiology, 345, 525-532.

Hultman, E. & Spriet, R.L. (1986). Skeletal muscle metabolism, contraction force and glycogen utilization during prolonged electrical stimulation in humans. Journal of Physiology, 374, 493-501.

Jones, P. & Pearson, J. (1969). Anthropometric determination of leg fat and muscle plus bone volumes in young male and female adults. Journal of Physiology, 204, 63-66.

Kim, C.K., Strange, S., Bangsbo, J., & Saltin, B. (1995a). Skeletal muscle perfusion in electrically induced dynamic exercise in humans. Acta Physiologica Scandinavia, 153, 279-287.

Kim, C.K., Bangsbo, J., Strange, S., Karpakka, J., & Saltin, B. (1995b). Metabolic response and muscle glycogen depletion pattern during prolonged electrically induced dynamic exercise in man. Scandinavian Journal of Rehabilitative Medicine, 27, 51-58.

Kots, Y. (1977). Lecture notes at the Canadian-Solviet exchange. Symposium on Electrical Stimulation of Skeletal Muscles. Concordia University, pp 6-15.

Lohman, T.G., Roche, A.F., & Martorell, R. (1988). Anthropometric Standardization Reference Manual Champaign Illinois: Human Kinetics Books.

Loiselle, D.S. & Walsmley, B. (1982). Cost of force development as a function of stimulis rate in rat soleus muscle. American Journal of Physiology, 243, C242-246.

Maxwell, L.C., Barclay, J.K., Mohrman, D.E., & Faulkner, J.A. (1977). Physiological characteristics of skeletal muscles of dogs and cats. American Journal of Physiology, 233, C14-C18.

McArdle, W.D., Katch, K. I., & Katch, V.L. (1991). Exercise Physiology: Energy, Nutrition and Human Performance (3rd Ed). Philadelphia: Lea & Febiger.

Miller, B.F. & Keane, C. (1987). Encyclopedia and Dictionary of Medicine, Nursing, and Allied Health, Philadelphia: W.B. Saunders Company.

Nelson, R.M. & Currier, D.P. (1991). Clinical Electrotherapy, (2nd Ed.) Connecticut: Appleton & Lange Publishers.

Néron, J.F. & Simoneau, J.A. (1994). Oxygen uptake of the knee extensor muscles induced by neuromuscular low frequency electrical stimulation. Canadian Journal of Applied Physiology, 19, (Supplement), 33P.

Petrofsky, J.S. & Phillips, C.A. (1983). Active physical therapy: a modern approach to rehabilitation therapy. Journal of Neurology and Orthopedic Surgery, 4, 165-173.

Poehlman, E.T. (1989). A review: exercise and its influence on resting energy metabolism in man. Medicine and Science in Sports and Exercise, 21, 515-525.

Randall, B.F. , Imig, C.J., & Hines, H.M. (1953). Effect of electrical stimulation upon blood flow and tempeture of skeletal muscle. American Journal of Physical Medicine, 32, 22-26.

Sahlin, K.L., Edstrom, L., Sjoholm, H., & Hultman, E. (1981). Effects of lactic acid accumulation and ATP decrease on muscle tension and relaxation. American Journal of Physiology, 240, (Cell Physiology), C121-126.

Saltin, B. (1985). Hemodynamic adaptations to exercise. American Journal of Cardiology, 55, 42D-47D.

Simoneau, J.A. (1989). Energy expenditure of the human knee extensor muscles induced by neuromuscular low frequency electrical stimulation. Canadian Journal of Sport Sciences, 14, 135.

Siff, M. (1990). Applications of electrical stimulation in physical conditioning: A review. Journal of Applied Sport Science Research, 4, 20-26.

Sjoholm, H., Sahlin, K., Edstrom, L., & Hultman, E. (1983). Quantitative estimation of anaerobic and oxidative energy metabolism and contraction characteristics in intact human skeletal muscle in response to electrical stimulation. Clinical Physiology, 3, 227-239.

Solomonow, M. (1984). External control of the neuromuscular system. IEEE Transactions on Biomedical Engineering, 31, 752-763.

Song, T.M.K., Hodgkinson, R., Stoot, F., & Porter, J. (1990). Effects of electrical stimulation and isometric exercise on venous blood values and contraction torque. Proceedings of the 1988 Seoul Olympic Scientific Congress Organizing Committee. pp 19-26.

Song, T.M.K., Guthrie, B., Newhouse, D., & Newhouse I. (1991). Effect of neuromuscular electrical stimulation on energy expenditure. Proceedings of the 24th Annual Meeting of the Canadian Association of Sport Sciences. p. 23.

Spriet, L.L., Soderlund, K., Bergstom, M., & Hultman, E. (1987). Anaerobic energy release in skeletal muscle during electrical stimulation in men. Journal of Applied Physiology, 62, 611-615.

Thériault, R., Thériault, G., & Simoneau, J. (1994). Human skeletal muscle adaptation in response to chronic low-frequency stimulation. Journal of Applied Physiology, 74, 1885-1889.

Tortora, G. (1989). Principles of Human Anatomy (5th Ed) New York:Harpen Collins Publishers.

Trimble, M.H. & Enoka, R.M. (1991). Mechanisms underlying the training effects associated with neuromuscular stimulation. Physical Therapy, 71, 273-280.

Underwood, F.B., Kremser, G.L., Finstuen, K., & Greathouse (1990). Increasing involuntary torque production by using TENS. Journal of Orthopedic Sports Physical Therapy, 12, 101-104.

Wilson, D.F. (1995). Energy metabolism in muscle approaching maximal rates of oxygen utilization. Medicine in Science in Sports and Exercise, 27, 54-59.

Windsor, R.E., Lester, J.P., & Herring, S.A. (1993). Electrical stimulation in clinical practice. The Physician and Sportsmedicine, 21, 83-89.

Zicot, M. & Rigaux, P. (1995). Effect of the frequency of neuromuscular electric stimulation of the leg on femoral arterial blood flow. Journal des Maladies Vasculaires, 20, 9-13.

APPENDIX A

CONSENT FORM

1. Effects of Neuromuscular Electrical Stimulation of Various Frequencies and Intensities on Energy Expenditure.

2. I ____________________ consent to take part in a study which will examine the effects of Neuromuscular Electrical Stimulation of Various Frequencies and Intensities on Energy Expenditure.

   1) measurements of height, weight, girth, and thickness of skinfolds.

   2) neuromuscular stimulation on the quadriceps muscles at intensities of 25, 50, 75, and 100 mA and frequencies of 8, 12, 20 and 50 Hz.

3. I understand that I will take the above tests and that I have the option to stop the test(s) at any time and/or omit any part of any test. I also understand that I may experience localized discomfort in the quadricep muscles as a result of the tests. In agreeing to these tests, I accept all responsibility and waive my legal recourse against Lakehead University and members of their staff from any and all claims resulting from personal injuries sustained from these tests. I understand that any data resulting which might be of a personal nature will be confidential. I further consent to the use of information obtained from these tests by Lakehead University.

I have read and understand the above.

____________________	____________________	____________
Name (print)	Signature	Date

____________________	____________________	____________
Witness (print)	Signature	Date

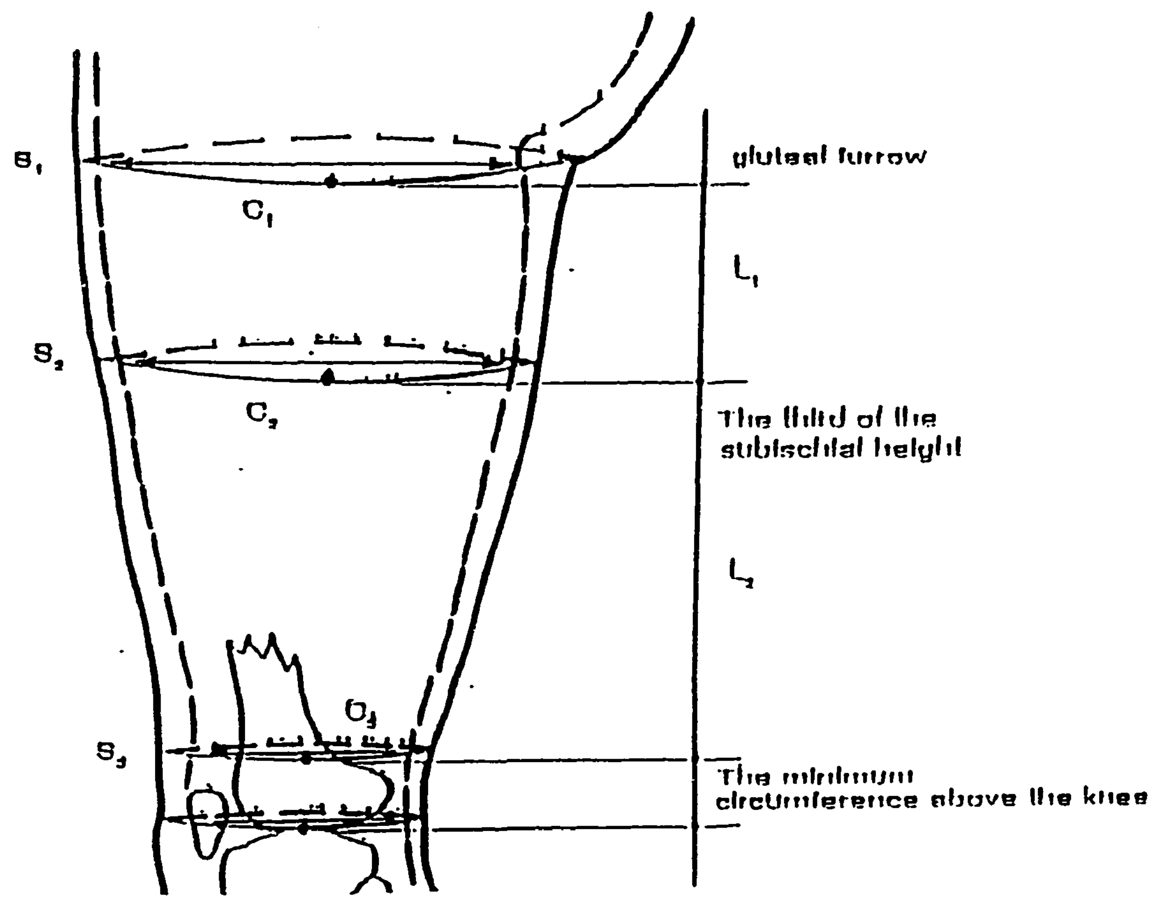
I have explained the nature of the study to the subject and believe he has understood it.

____________________	____________________	____________
Name (print)	Signature	Date

APPENDIX B

ESTIMATED MUSCLE VOLUME AND MUSCLE MASS OF THE KNEE EXTENSOR MUSCLES

L: length
C: circumference
S: skinfold



Muscle volume (Jones & Pearson, 1969)

$$\frac{\{L_1[(C_1-\pi S_1)^2+(C_1-\pi S_1)(C_2-\pi S_2)+(C_2-\pi S_2)^2]+L_2[(C_2-\pi S_2)^2+(C_2-\pi S_2)(C_3-\pi S_3)+(C_3-\pi S_3)^2]\}}{12\pi}$$

Muscle mass (Saltin, 1985)

0.307 x Muscle volume (L) + 0.353

APPENDIX C

ELECTRODE PLACEMENT

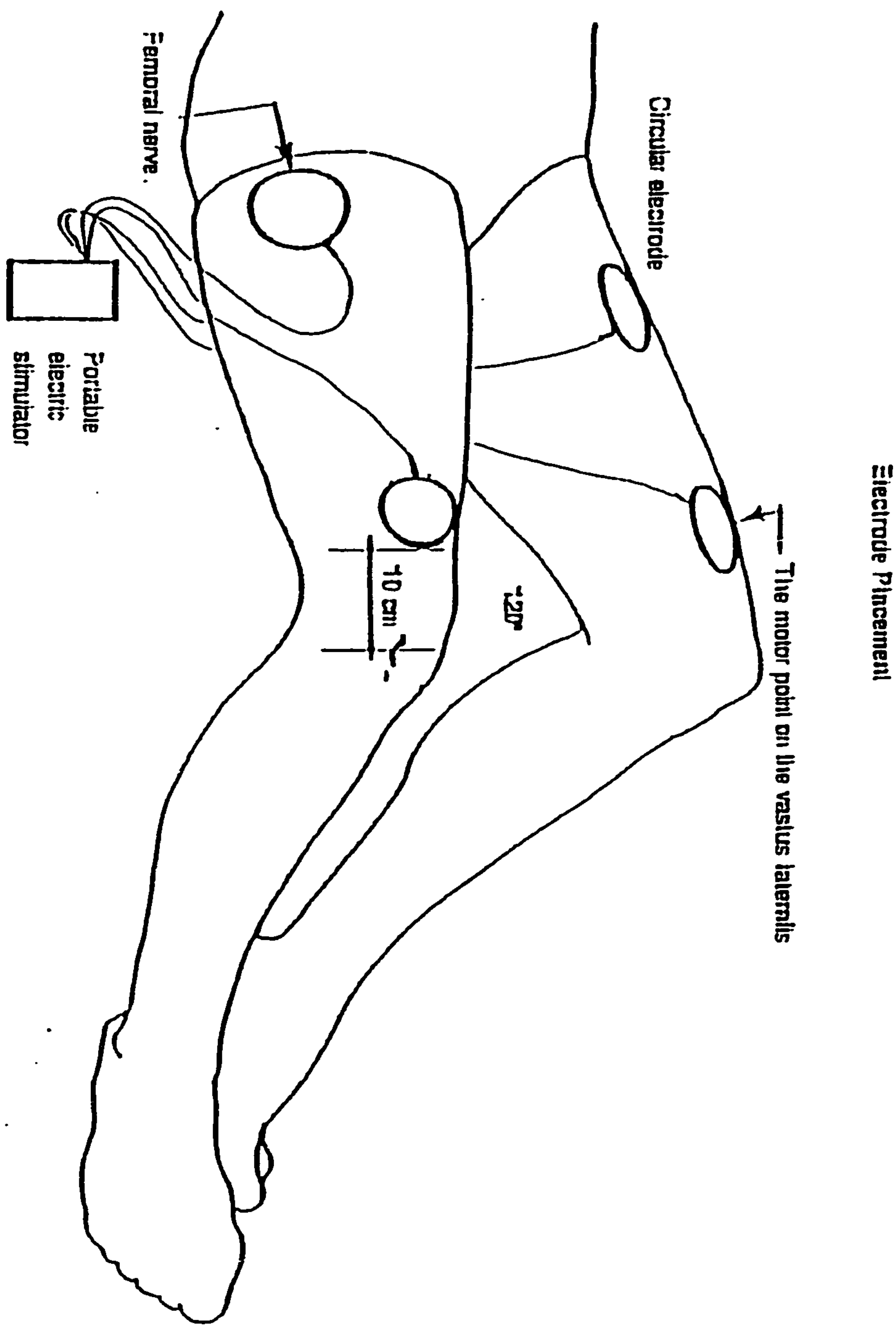
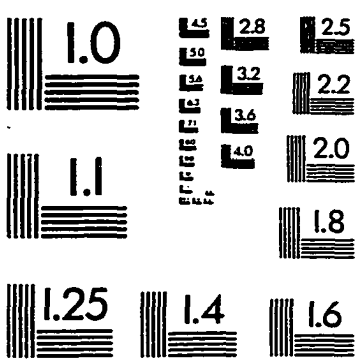


IMAGE EVALUATION
TEST TARGET (QA-3)



150mm

6″

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