Effect of Cryotherapy on Neuromuscular Electrical Stimulation

A Review of the Literature

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ABSTRACT

Neuromuscular electrical stimulation (NMES) has been shown to be an effective technique to strengthen muscle following musculoskeletal injury or surgery. A limitation of NMES is the discomfort caused by the strong electrical contractions required for effective strength gains. This article explores whether the application of cryotherapy over muscle affects the ability of the muscle to contract in response to NMES and whether the reduction in discomfort of the stimulus enables greater force production. Eleven studies that met the inclusion criteria were reviewed. This review found that short-duration application of cryotherapy can improve tolerance to strong contractions elicited by NMES for muscle strengthening; however, longer-duration applications may affect muscle force production. More studies are needed to determine the effect of cryotherapy on force production of muscle during NMES and whether greater increases in strength can be achieved.

Neuromuscular electrical stimulation (NMES) is a widely used intervention for rehabilitation of weak or damaged muscle. Studies support the use of this technique for strengthening muscle following ligament repairs of the knee and total knee joint arthroplasties.[1-4] The typical clinical approach is to place electrodes on the skin overlying the motor points of the muscle, which are usually defined as the location over the muscle where the motor nerve to the muscle is most accessible. The intensity of the stimulation depends on the amplitude, duration, and frequency of the electrical pulses, or bursts. A high-amplitude, long-pulse duration stimulus is required to achieve a contraction that is at least 50% of maximal voluntary contraction (MVC). This stimulus may not be tolerated by the patient. Farquhar and Snyder-Mackler[5] identified patient discomfort as the limiting factor in using NMES in clinical settings, especially "when high contractile forces are sought for strength training regimens." Most clinical uses of NMES are for strengthening of weak or injured muscle. The use of NMES for uninjured individuals is uncommon because strength gains can be achieved by exercise programs without the use of NMES.

Patient tolerance to NMES for muscle strengthening depends primarily on the type of electrical current chosen for the treatment and the patient's pain coping style.[5] Some patients can tolerate burst mode alternating current (Russian stimulation) NMES, whereas other patients prefer biphasic pulsed NMES. Pain coping style varies from those patients who focus on the discomfort of NMES and those who focus on the benefits of the treatment and are willing to tolerate discomfort. Patients who focus on the discomfort of NMES require a blunting strategy to decrease their perception of pain. Strategies for blunting the perception of pain can include distraction by listening to music or interventions that interrupt nociception to the central nervous system. Modalities such as cryotherapy applied during or prior to NMES may be an effective blunting strategy; however, decreasing the temperature of tissues overlying a muscle or of the muscle itself may affect the ability of NMES to achieve a muscle contraction. The effect of

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TABLE 1

Keywords Used in the Current Study Database Searches

Electrical stimulation
Neuromuscular electrical stimulation
Cryotherapy
Temperature
Muscle contraction
Muscle contractility

cold application on muscle contraction may negate any benefit that may be achieved by improvement of threshold for electrical contraction of muscle.

The literature is inconclusive regarding the effect of cryotherapy alone on muscle strength. Some studies report a decrease in muscle strength following the application of cold,[6-12] whereas others report an increase[13-15] or no change.[16,17] Does the application of superficial cold modalities on the skin overlying a muscle affect the ability of NMES to achieve high-level muscle contractions necessary for strength gains? Or does cryotherapy permit patients to better tolerate the high current levels required for effective strengthening of muscle?

Neuromuscular electrical stimulation is indicated for patients who are unable to achieve the strong voluntary muscle contractions required for muscle strengthening programs.[5] These patients may be limited by pain or swelling (or both) that inhibits voluntary muscle contractions. A significant central nervous system component known as reflex inhibition, or activation failure, may inhibit muscle contraction. Reflex inhibition can limit the voluntary contraction of muscle and prevent the achievement of strong voluntary contractions needed for strengthening. Neuromuscular electrical stimulation can help overcome reflex inhibition, enabling strong muscle contractions.[5]

Muscle contractions caused by NMES are not the same as voluntary contractions, although the clinically observed response may appear to be the same. Voluntary contractions occur by recruitment of alpha motoneurons in an orderly sequence, beginning with the smallest and progressively recruiting larger motoneurons as more force is required.[18] Electrically induced contractions were originally thought to recruit alpha motoneurons in a pattern opposite to voluntary contractions[19]; however, it is now thought that NMES recruits both small and large alpha motoneurons simultaneously.[18] Volitional motor unit recruitment occurs from slow-twitch, fatigue-resistant fibers to fast-twitch fatigue-resistant fibers to fast-twitch, fatiguable fibers. Electrically induced contractions were originally thought to follow the opposite pattern; however, it more likely recruits all types of fibers simultaneously.

High-contraction force levels are necessary to achieve strength gains when performing NMES. These high force levels require stimulation frequencies higher than critical fusion frequency (tetany); however, high frequencies result in greater muscle contraction fatigue.[19] Use of on/off cycles (eg, 10 seconds on, 50 seconds off) during NMES helps to limit muscle fatigue. The therapeutic benefit of NMES is the achievement of strength gains for patients who are unable to perform effective voluntary muscle strengthening exercises.

LITERATURE REVIEW

A systematic review of the literature was performed to determine the effect of cryotherapy on the ability of NMES to achieve the high-force muscle contractions required for effective muscle strength gains. The following electronic databases were searched by the 3 authors: Cochrane Central Register of Controlled Trials, Cochrane Database of Systematic Reviews, MEDLINE, PubMed, CINAHL, and ProQuest Health and Medical Complete. Keywords used in the search are listed in Table 1. The authors independently screened the titles and abstracts of the studies found in these databases for eligibility for inclusion in this review. A total of 38 studies that included at least 2 of the keywords listed in Table 1 and were published in English between January 1980 and July 2010 were retrieved in full text. Each author then independently reviewed the studies using the following criteria for inclusion in this review: was performed on human participants; used NMES to contract muscle; applied cryotherapy during or prior to NMES; and described the effect of cryotherapy on muscle contraction. Eleven studies met these inclusion criteria. Each author independently assessed the methodological quality of each of the 11 studies using the Jadad criteria[20] and Sackett levels of evidence[21] (Table 2) to score each criteria. The authors met and discussed their independent assessment to achieve consensus on the quality of each study (Table 3). Six studies were rated as Sackett level 2B, the remaining five studies were rated as level 3B or level 4.

FINDINGS

Measurement of Tissue Temperature

Each of the 11 studies reviewed applied a superficial cryotherapy modality to the skin surface in an attempt to decrease the temperature of the skin or underlying muscle. Two studies measured muscle temperature via a thermistor probe inserted into the muscle.[22,23] Six studies measured superficial skin temperature. Petrofsky et al[24] measured skin temperature with a BioPac skin temperature thermistor probe (TSD202B; Biopac Systems Inc, Goleta, California). De Ruiter et al[25] and De Ruiter and De Haan[26] used a thermocouple secured to the skin over the adductor pollicis muscle and calculated muscle temperature (Tm) using the formula Tm = 1.02 Ts + 0.89 (where Ts is skin temperature). Ranatunga et al[27] monitored skin temperature with a thermocouple encased in aluminum foil placed over the central area of the muscle. Miller and Webers[28] used a digital thermometer placed between 2 motor points on the skin of the thigh. Peiffer et al[29] measured skin temperature using skin thermistors attached by adhesive tape to 4 locations on the body. They also measured rectal temperature using a disposable rectal thermometer. Three studies did not measure skin or muscle temperature.[30-32]

NMES Technique and Measurement of Response

Most of the studies performed direct stimulation of the target muscle by placing electrodes on the skin over the muscle to be stimulated. Exceptions were the study by Ranatunga et al,[27] who placed electrodes over the forearm and elbow to stimulate the first dorsal interosseous muscle via the ulnar nerve, and the studies by Davies et al[22] and Davies and Young,[23] who stimulated the adductor pollicis muscle by percutaneous stimulation of the ulnar nerve at the wrist. Table A (available as supplemental material in the online version of this article) provides details on the NMES parameters used in each study.

An isokinetic dynamometer was used in 4 studies[28-30,32] to measure isometric torque produced by the quadriceps to determine the response of muscle to NMES. Davies et al[22] and Davies and Young[23] used a leg dynamometer to determine MVC for the triceps surae. They also recorded twitch responses, which were stored on an oscilloscope,[22] and maximal jumps on a force platform and maximal work on a force bicycle at various constant velocities.[23] Rafolt et al[31] used a "specially developed ankle dynamometer" to determine ankle plantarflexion MVC during NMES of the triceps surae. Ranatunga et al[27] measured abduction of the index finger against a force transducer, which was recorded on a storage oscilloscope, and De Ruiter et al[25] and De Ruiter and De Haan[26] measured adduction of the thumb against a vertical pin attached to a strain gauge. Petrofsky et al[24] recorded the stimulation current threshold in mA for the quadriceps, biceps, and gastrocnemius muscles.

TABLE 2

Sackett Levels of Evidence

1A	Systematic review of randomized controlled trials (RCTs)
1B	RCTs with narrow confidence interval
1C	All or none case series
2A	Systematic review cohort studies
2B	Cohort study/low quality RCT
2C	Outcomes research
3A	Systematic review of case-controlled studies
3B	Case-controlled study
4	Case series, poor cohort case controlled
5	Expert opinion

Temperature Changes of Tissues in Response to Cryotherapy

Interventions used in the 11 studies included in this review are summarized in Table A. The type of cryotherapy selected to cool tissues included ice bags,[30,31] crushed ice wrapped in a wet towel,[32] ice massage,[28] immersion of body part in cold water,[22,23,25-27,29] and cold packs with one layer of towel between the skin and the cold pack.[24] The duration of cold modality application varied greatly, from 2 minutes[24] to 45 minutes.[23] Eight of the 11 studies reviewed applied cryotherapy prior to NMES of the cooled muscle. The amount of cooling of skin or muscle tissue in the reviewed studies varied depending on the type of cryotherapy and method of measurement. Peiffer et al[29] found a 12°C decrease in skin temperature and an approximate 1.1°C decrease in rectal temperature following cold water immersion of the body (up to the mid-sternum). Petrofsky et al[24] measured skin temperature and found a 15°C decrease following a 5-minute application of a cold pack to the skin. DeRuiter et al[25] and De Ruiter and De Haan[26] estimated muscle temperatures decreased as low as 11.8°C following immersion of the hand in a cold water bath. Ranatunga et al[27] estimated

TABLE 3

Scoring of Studies Based on Sackett Levels of Evidence (Consensus of 3 Authors)

	JADAD CRITERIA QUESTION NUMBER								
STUDY	1	2	3	4	5	6	7	8	SCORE[a]
Peiffer et al (2009)[29]	N	N	N	N	N	Y	Y	Y	2B
Petrofsky et al (2008)[24]	N	Y	N	N	N	N	UD	Y	2B
Van Lunen et al (2003)[30]	N	Y	N	N	N	Y	Y	Y	2B
DeRuiter & De Haan (2000)[26]	N	N	N	N	N	Y	Y	Y	4
DeRuiter et al (1999)[25]	N	N	N	N	N	Y	UD	Y	2B
Rafolt et al (1999)[31]	N	N	N	N	N	Y	Y	Y	3B
Durst et al (1991)[32]	N	N	Y	N	N	Y	Y	N	2B
Miller & Webers (1990)[28]	N	Y	N	N	Y	N	Y	Y	2B
Ranatunga et al (1987)[27]	N	N	N	N	N	UD	UD	Y	4
Davies & Young (1983)[23]	N	N	N	N	N	Y	Y	Y	3B
Davies et al (1982)[22]	N	N	N	N	N	Y	Y	Y	4

Abbreviations: N, no; Y, yes; UD, unable to determine item criteria number.
[a] Refer to Table 2 for descriptions of these scores.

a decrease in muscle temperature from 35°C to 12°C following immersion of the hand in an ice water bath. Davies et al[22] and Davies and Young[23] found that muscle temperature decreased an average of 10°C following immersion of the limb in cold water for 30 to 45 minutes. Miller and Webers[28] measured skin temperature between electrodes following 2 minutes of ice massage and found no change in temperature.

Effects of Cooling of Skin and Muscle on NMES

Most of the studies in this review found that cooling of tissues prior to NMES dampened the contractile response of the muscle, with a few exceptions. Davies et al[22] and Davies and Young[23] found decreased twitch tension and decreased tetanic force production when the triceps surae were electrically contracted following immersion of the leg in cold water. This effect was most pronounced at higher frequencies of stimulation (⩾40 Hz). Ranatunga et al[27] demonstrated that the cooling of tissues of the hand over the first dorsal interosseous muscle decreased electrically elicited muscle twitch tension and slightly decreased peak muscle tension. They noted that twitch tension of the first dorsal interosseous muscle decreased sharply when cooled below 25°C. Rafolt et al[31] found a slower rate of force development and decreased relative dynamic force amplitude when the triceps surae was electrically contracted following application of ice bags over the muscle belly of one participant. The duration of application of the ice bags was not specified, and the temperature of the tissues was not measured; therefore, the effect of the ice application cannot be certain. De Ruiter et al[25] and De Ruiter and De Haan[26] found that the rates of electrically elicited contraction force development were slower and that maximum twitch and isometric forces were significantly lower when tissues were cooled. Contractile force following cryotherapy was progressively depressed at stimulation frequencies >50 Hz. Peiffer et al[29] superimposed NMES to the quadriceps of participants who were performing a maximal voluntary contraction following a 20-minute immersion of the leg in cold (14.3°C) water. A significant decrease in isometric torque was produced by the muscle compared with preimmersion measurements; however, there was no significant difference between participants who performed maximum voluntary contractions without NMES and those who had superimposed NMES.

Some of the studies reviewed found that cryotherapy may improve tolerance to NMES and enhance muscle function. De Ruiter and De Hann[26] found that there was less fatigue of muscle when muscle temperature was decreased from 37.1°C to 22.2°C; however, maximal isometric force and muscle-shortening velocity significantly decreased. Three studies reported an increased tolerance to NMES following cooling of tissues.[24,28,32] Van Lunen et al[30] found that participants who had ice bags placed over electrodes during NMES tolerated a significantly greater stimulation intensity than did those in a control group; however, there was no difference in isometric peak torque between groups. Miller and Webers[28] found a significant increase in torque produced by NMES following a 2-minute ice massage over the motor points of the vastus medialis and rectus femoris muscles. Petrofsky et al[24] noted that less current was needed to achieve motor threshold (ie, the beginning of a muscle contraction) following a 5-minute application of cold packs to the skin. Muscle force production was not measured in their study.[24]

DISCUSSION

The authors of this review searched the literature for studies on the combined effects of cryotherapy and NMES published in the past 30 years. We found 11 studies that met our inclusion criteria for review. Table A summarizes the outcomes and conclusions for each of the studies included in this review.

The cooling of tissues by application of cryotherapy modalities may affect the response of muscle to the application of NMES. Most of the studies included in this review found a decrease in twitch tension and tetanic force production when the tissues overlying the muscle or the target muscle temperature were decreased by at least 8°C prior to electrical stimulation.[22,23,25-27,29,31] This temperature decrease may lessen the effectiveness of NMES when the clinical goal is to increase muscle strength. Other studies indicate that the effects of decreased tissue temperature on muscle contraction force may be balanced by improved tolerance for higher levels of stimulation intensity.[24,28,30,32] Inhibition of muscle contractile force caused by application of cryotherapy may be minimized by the improved tolerance for higher-level stimulation necessary for strength gains in muscle. Tolerance of high-amplitude levels of NMES is desirable to obtain maximal muscle force production, which will enable training following the overload principle. Strengthening of muscle following the overload principle requires muscle contractions at greater than 75% of MVC for a low number of repetitions.[19] NMES is capable of achieving greater than 75% MVC.[33]

The sequence of cryotherapy and NMES may affect the response of the muscle. All but one of the studies applied cryotherapy prior to NMES. Van Lunen et al[30] were unable to achieve greater torque production when they applied ice bags over electrodes during NMES. Whether cooling of tissues during NMES will inhibit or facilitate achievement of muscle strength gains needs further investigation.

Factors that likely determine the effect of cryotherapy on NMES include the depth of cooling, the duration of cooling, type of modality, amount of adipose tissue between the skin and muscle, and effects on blood flow and skin sensation. The depth of the cooling effect when cryotherapy modalities are applied to the skin primarily depends on the duration of the application and the type of modality. Temperature of a muscle at a depth of 4 cm can be lowered by an average of 1.2°C within 5 minutes following application of cold[34]; however, it can take as long as 30 minutes for the temperature of the muscle to decrease by 3.5°C.[35] Crushed ice in a bag or in water is more effective in cooling deeper tissues than frozen gel packs or cold water baths.[36] Brief applications of cryotherapy alone (≤5 minutes) have been shown to facilitate muscle isometric strength.[28] Given that short duration of cryotherapy is unlikely to affect muscle temperature, facilitation of muscle contraction strength must be secondary to neuromuscular or psychological effects. This may explain the results of the studies by Petrofsky et al[24] and Miller and Webers[28] in which cold packs were applied for 5 minutes and ice massage was performed for 2 minutes, respectively, which resulted in facilitation of muscle response to NMES. The thickness of the fat tissue between the skin and the muscle will affect the degree of cooling of subcutaneous tissues.[37] Petrofsky et al[24] measured skin and fat thickness of their participants using high-resolution ultrasound. They found no significant difference in skin thickness in any of the sites examined. They did find a significant difference in fat thickness between male and female participants, as well as a correlation between fat thickness and the threshold for electrical contraction of muscles. The threshold for female participants was significantly higher than for male participants, which correlated with higher levels of fat thickness in the female participants.

Cryotherapy can affect blood flow to superficial and deep tissues. The immediate response to cold application on the skin is vasoconstriction of cutaneous blood vessels, resulting in decreased blood flow.[38] Petrofsky et al[24] monitored skin blood flow with a laser doppler flow meter. Participants who received hot packs for 5 minutes had increased skin blood flow and required more NMES current to reach threshold for muscle contraction. Participants who received cold packs for 5 minutes had decreased skin blood flow and required less current to reach muscle contraction threshold. The authors thought the changes in blood flow secondary to the application of hot or cold packs affected the resistance to current flow in the skin. The application of cold packs to the skin decreased skin blood flow, which increased skin electrical resistance (blood has lower electrical resistance than surrounding tissues). The increase in resistance shifted electric current flow away from the skin and increased electric current flow to the muscle. As a result, less current was needed to achieve the muscle contraction threshold. The study by Petrofsky et al[24] did not assess the effects of cryotherapy on NMES force production, nor did it assess participants' tolerance to NMES.

Application of cryotherapy prior to or during NMES may affect skin sensation. It is well known that cooling of the skin can elevate pain threshold and reduce pain. Application of cold to the skin will decrease sensory and motor conduction velocities of peripheral nerves.[39,40] Neuromuscular electrical stimulation will cause depolarization of sensory receptors in the skin, resulting in a tingling or prickling sensation that will increase in intensity as the current is increased. At higher levels of current, this sensation becomes uncomfortable and may be painful. Application of cryotherapy prior to or during NMES will likely cause a numbing effect of the skin sensory receptors, resulting in greater tolerance for the intense tingling or prickling sensation created by NMES. The numbing effect of the cold on skin sensation may have been a factor in the studies that found an increase in tolerance for electrical contraction of muscle. [28,30,32] This numbing effect may have blunted the discomfort of NMES and helped participants tolerate greater amounts of electrical current. The slowing of motor conduction velocities following cold application may have been a factor in the studies that found a decrease response to electrical contraction of muscle. [22,23,25-27,29,31]

The studies in this review indicate the effects of cryotherapy on NMES for single applications of these interventions. The need for cryotherapy prior to or during NMES may change over time, given that tolerance to NMES may be affected by habituation to the stimulation over time. More studies are needed to determine the effect of repeated applications of cryotherapy and NMES to replicate clinical practice.

IMPLICATIONS FOR CLINICAL PRACTICE

Short-duration cryotherapy may be a useful adjunct to improve tolerance for NMES when the goal of treatment is to strengthen muscle. Improved tolerance for NMES may allow greater torque production and greater increases in muscle strength. However, more studies are needed to determine whether cryotherapy enhances or inhibits NMES-generated torque production.

CONCLUSION

This review of the literature from January 1980 to July 2010 on the effect of cryotherapy on NMES found 11 studies that met the inclusion criteria. On the basis of this review, clinicians should consider the following when performing NMES for muscle strengthening:

- Short-duration application (⩽5 minutes) of cold modalities to the skin overlying a muscle may decrease the amplitude required to achieve contraction during NMES.
- Long-duration application (⩾20 minutes) of cold modalities to the skin overlying a muscle may decrease the maximum twitch response and tetanic response during NMES.
- Application of cold modalities to the skin prior to or during NMES may increase the tolerance for higher levels of current; however, higher tolerance may not result in higher isometric torque.
- Type of cold modality, length of time for application of cold, subcutaneous adipose tissue thickness, skin blood flow, type of electrodes, and skin preparation are factors that need to be considered when applying cryotherapy during or prior to NMES for muscle strengthening.

FURTHER RESEARCH

The results of this literature review indicate the need for more studies to determine the following:

- Will improved tolerance to NMES result in greater strength gains of stimulated muscle?
- Which type of cryotherapy is most effective in improving tolerance to NMES, and which is most practical for clinical application prior to NMES?
- What is the optimum time of application of cryotherapy prior to NMES?
- Which method of clinical application of cryotherapy

is most effective in improving tolerance to NMES: application prior to NMES or application during NMES?

- What effect do skin and adipose tissue thickness and skin blood flow have on the effect of cryotherapy and tolerance for NMES?
- Will other therapeutic modalities (superficial heat, diathermy, transcutaneous electrical nerve stimulation, massage) improve tolerance for NMES for muscle strengthening? ■

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Table A

Description of Reviewed Studies

Study	Subjects	Thickness of Adipose Tissue	Cryotherapy Technique	Waveform and Device	Electrodes and Skin Preparation	Pulse Frequency	Pulse Duration	Technique	Outcomes	Conclusions
Peiffer et al (2009)	10 well-trained male cyclists, mean age = 27 years.	Thickness not described; subjects described as 10 well-trained male cyclists.	Cold water immersion (to midsternal levels) for 20 minutes prior to NMES, water temp 14.3˚C.	Square wave using ETS model 4000 device.	Bipolar, over rectus femoris muscle, electrodes and skin preparation not described.	100 Hz	Not described	Applied for 1 second during a 5-sec MVIC.	Significant decrease in torque produced following cold water immersion compared with control group. No difference in torque between MVIC and NMES.	Cold water immersion has a negative effect on neuromuscular function, resulting in reduction in isometric strength.
Petrofsky et al (2008)	10 males and 15 females, mean age = 24 years.	Subcutaneous fat 0.6 to 0.9 cm, females thicker than males; for every .1 cm increase in fat current needs to be increased by 4.4 mA.	Cold packs applied over biceps, gastrocnemius, and quadriceps for 5 minutes prior to NMES.	Biphasic sine wave using a "current control challenge 8000 powered muscle stimulator" (MPTS, Inc, Tustin, California)	Monopolar, over motor point, electrodes, and skin preparation not described.	30 Hz	100 µsec	Current necessary to elicit the beginning of a muscle contraction.	Significant less current needed to achieve motor threshold following cold packs. Changes in motor threshold correlated with changes in blood flow.	Changes in blood flow following application of cold packs will determine the amount of current needed to achieve motor threshold.

Study	**Subjects**	**Thickness of Adipose Tissue**	**Cryotherapy Technique**	**Waveform and Device**	**Electrodes and Skin Preparation**	**Pulse Frequency**	**Pulse Duration**	**Technique**	**Outcomes**	**Conclusions**
Van Lunen et al (2003)	38 subjects, 20 males, 18 females.	Thigh skinfold measured to estimate "thickness of thigh": females (13.2 ± 3.2 mm) were thicker than males (8.9 ± 3.3 mm).	Two 1-gallon plastic bags filled with crushed ice were placed over the anterior thigh, 1 over each electrode.	No waveform described, used Forte CPS Series device (Chattanooga Corporation, Chattanooga, Tennessee).	Bipolar, over motor points, 2-inch self-adhering electrodes, and skin preparation not described.	35Hz	200 µsec	NMES applied for 20 minute duration, current was increased every 4 minutes up to max pain tolerance.	Test group (ice) tolerated significant-ly greater NMES intensity than control group (no ice). No difference in isokinetic peak torque between groups.	Application of ice over quadriceps during max tolerated NMES may increase tolerance for higher levels of NMES intensity; however, this may not result in higher torque production.
De Ruiter & De Haan (2000)	10 healthy subjects, mean age = 21 years, 9 females and 1 male.	Not described.	Hand and forearm immersed in water bath for 20 minutes at 4 different temperatures: 17˚C, 22.5˚C, 30.5˚C, and 45˚C, prior to NMES.	Constant current unidirectional square wave pulses using Digitimer model DS7 device (Digitimer Ltd, Welwyn Garden City, UK).	Percutaneous	Variable, 1 to 300 Hz	100 µsec	Stimulation of the ulnar nerve at the wrist, current set at 30% above max isometric tetanic force.	At lower temperatures max isometric F and max muscle shortening velocity significantly decreased, and there was less fatigue of muscle.	Immersion of hand in cold water prior to NMES of the adductor pollicis will likely decrease F production and fatigue of the muscle.
De Ruiter et al (1999)	15 healthy subjects, mean age = 21 years, 8 males, 7 females.	Not described.	Hand and forearm immersed in water bath for 20 minutes at 4 different	Constant current unidirectional square wave pulses using Digitimer	Percutaneous	Variable, 1 to 300 Hz	100 µsec	Stimulation of the ulnar nerve at the wrist, current set at 30%	Rates of force development and relaxation were slower	Immersion of hand in cold water prior to NMES at the wrist may inhibit muscle force

Study	**Subjects**	**Thickness of Adipose Tissue**	**Cryotherapy Technique**	**Waveform and Device**	**Electrodes and Skin Preparation**	**Pulse Frequency**	**Pulse Duration**	**Technique**	**Outcomes**	**Conclusions**
			temperatures: 17˚C, 22.5˚C, 30.5˚C, and 45˚C, prior to NMES.	model DS7 device (Digitimer Ltd, Welwyn Garden City, UK).				above max isometric tetanic force.	at colder temperatures and max twitch and isometric forces were significantly lower.	production of the adductor pollicis and poststimulation relaxation.
Rafolt et al (1999)	6 healthy males, ages 33-45 years.	Not described.	Two ice bags placed over muscle belly of triceps surae between the electrodes.	Biphasic pulses using MYOSTIM device (BMTP, University of Vienna, Vienna, Austria).	Above and below the belly of the triceps surae muscle, square electrodes, type and skin prep not described.	Started at 25 Hz, increased stepwise by 2.5 Hz up to 30 Hz.	1 ms	Series of pulses to achieve 20% MVC, then another series to achieve 40% MVC.	Only one subject had application of cold to triceps surae; cooling of muscle decreased fusing frequency and the relative dynamic F amplitude during NMES.	Cooling of muscle may affect rate of response and force production when electrically contracted.
Durst et al (1991)	20 male active duty US military personnel, mean age = 26 years.	Thickness not described; subjects described as "healthy active duty male US military personnel, not overweight by military standards."	Crushed ice wrapped in a wet towel that had been immersed in 18˚C water was placed over the entire anterior thigh for 30 minutes.	No waveform described, used Electrostim 180-2 device (Electrostim USA Ltd, Joliet, Illinois).	Monopolar, over motor point, single-use gel electrodes, skin shaved prior to application.	250 Hz	Not described	Current in-creased to submax contraction and held for 5 sec., then in-creased to max toler-ance.	Better tolerance for NMES after ice, but not signifi-cant. No difference in torque production between group that	Application of ice to quads prior to NMES does not significantly affect tolerance or production of torque.

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									received ice and the group that did not.	
Miller & Webers (1990)	21 female students, age range = 20-27.	Estimated percent body fat by measuring circumference of limbs; 21 female subjects had body fat range of 18% to 27%.	Two minutes of ice massage over motor points of vastus medialis and rectus femoris muscles.	No waveform described, used Intelect VMS device (Chattanooga Corporation, Chattanooga, Tennessee).	Bipolar, over motor points, carbonized rubber electrodes covered with sponge, skin cleaned with alcohol and shaved.	35 Hz	200 μsec	Current in-creased to max toler-ance.	Significant increase in isometric torque for group that received both ice massage and NMES compared with NMES only group.	Application of ice massage prior to NMES may increase isometric torque output of quadriceps.
Ranatunga et al (1987)	4 subjects, not described.	Not described.	Hand placed in ice water bath.	Square pulses, no device identified.	Monopolar, large electrode over the forearm, smaller electrode over the ulnar groove at the elbow, metal plate anode and saline-soaked cathode, skin preparation not described.	Not described .	0 to 5 ms	Stimulation of the ulnar nerve at the elbow using supra-maximal intensity (approximately 50 V).	Cooling prior to stimulation lengthened contractions and slightly decreased peak amplitude and increased duration of contraction. Twitch tension decreased sharply at temperatures	Lower muscle temperatures may affect contraction characteristics of electrically stimulated muscle.

Study	Subjects	Thickness of Adipose Tissue	Cryotherapy Technique	Waveform and Device	Electrodes and Skin Preparation	Pulse Frequency	Pulse Duration	Technique	Outcomes	Conclusions
									that were below 25˚C.	
Davies & Young (1983)	5 healthy subjects, mean age = 22 years.	Not described.	Leg immersed in "iced" water at 0˚C for either 30 minutes or 45 minutes.	Not described.	Two 10x8-cm foil pads covered with tissue, skin preparation not described.	10, 20, and 40 Hz for 2 seconds each.	50 µsec	Series of pulses, progressive increase in voltage, applied to triceps surae at 30-sec intervals up to max tetanic tension.	Immersion of leg in cold water had no effect on tetany at lower frequencies; there was decreased tetany and MVC at 40 Hz and above. Decreased dynamic force values on force platform and bicycle following cold immersion.	Immersion of the leg in cold water prior to electrical stimulation of muscle may affect tetanic tension of the muscle and ability to generate dynamic contractile forces.
Davies et al (1982)	5 healthy subjects, mean age = 22 years.	Not described.	Leg immersed in "iced" water at 0˚C for either 30 minutes or 45 minutes.	Square wave using high voltage stimulator controlled by a Digitimer.	Bipolar, 1 over heads of gastroc-nemius, the other over the belly of the soleus, two 10x8 cm foil pads covered with tissue, skin	0.2, 2, and 10 Hz for twitch response; 10, 20, 50, and 100 Hz for 2 seconds each for	50 µsec	Max twitch tension was achieved by applica-tion of pulses at increasing voltage, then tetanic contrac-tions were	Cooling of muscle severely impaired tension develop-ment when stimulated at high frequencies (50 and 100	Immersion of the leg in cold water prior to electrical stimulation of muscle may affect the contraction response of the muscle.

Study	Subjects	Thickness of Adipose Tissue	Cryotherapy Technique	Waveform and Device	Electrodes and Skin Preparation	Pulse Frequency	Pulse Duration	Technique	Outcomes	Conclusions
					preparation not described.	tetanic contrac-tions; 20 Hz for fatigue test.		produced by an 8-sec stimulus train up to 80% MVC.	Hz); MVC and tetanic response were reduced at coldest tempera-tures.	

Abbreviations: NMES, neuromuscular electrical stimulation; MVIC, maximal voluntary isometric contraction; MVC, maximal voluntary contraction; max, maximal; F, force.