Eur J Appl Physiol (2011) 111:2501–2507
DOI 10.1007/s00421-011-2117-7

MINI REVIEW

Does electrical stimulation enhance post-exercise performance recovery?

Nicolas Babault · Carole Cometti · Nicola A. Maffiuletti · Gaëlle Deley

Received: 5 March 2011 / Accepted: 3 August 2011 / Published online: 17 August 2011

Abstract Elite sport requires high-volume and high-intensity training that inevitably induces neuromuscular fatigue detrimental for physical performance. Improving recovery processes is, therefore, fundamental and to this, a wide variety of recovery modalities could be proposed. Among them, neuromuscular electrical stimulation is largely adopted particularly by endurance-type and team sport athletes. This type of solicitation, when used with low stimulation frequencies, induces contractions of short duration and low intensity comparable to active recovery. This might be of interest to favour muscle blood flow and therefore metabolites washout to accelerate recovery kinetics during and after fatiguing exercises, training sessions or competition. However, although electrical stimulation is often used for recovery, limited evidence exists regarding its effects for an improvement of most physiological variables or reduced subjective rating of muscle soreness. Therefore, the main aim of this brief review is to present recent results from the literature to clarify the effectiveness of electrical stimulation as a recovery modality.

Keywords Sport · Performance · Muscle soreness · Strength

Communicated by Roberto Bottinelli.

This article is published as part of the Special Issue Cluster on the XVIII Congress of the International Society of Electrophysiology and Kinesiology (ISEK 2010) that took place in Aalborg, Denmark on 16-19 June 2010.

N. Babault · C. Cometti · G. Deley
Centre d'expertise de la Performance,
Faculté des Sciences du Sport,
Université de Bourgogne, BP 27877,
21078 Dijon Cedex, France

N. Babault (✉)
Faculté des Sciences du Sport,
Université de Bourgogne, BP 27877,
21078 Dijon Cedex, France
e-mail: nicolas.babault@u-bourgogne.fr

N. A. Maffiuletti
Neuromuscular Research Laboratory,
Schulthess Clinic, Lengghalde 2,
8008 Zurich, Switzerland

Introduction

Elite sport requires high-volume and high-intensity training. The stressful components of training as well as competitions repetition (more particularly in team sport) inevitably impair athletes' performance. This transitory fatigue state, which may last from several minutes to several days post-exercise (Martin et al. 2004), depends on peripheral changes occurring within the contractile apparatus distal to the motor point (at the muscle level) and/or on central changes leading to reductions of motor unit activation. Multiple mechanisms, such as metabolic disturbances (Pi, H^+,…), glycogen depletion or muscle damages may be involved (Gandevia 2001; Allen et al. 2008; Ament and Verkerke 2009). When considering that fatigue appears to be detrimental for optimal training and performance enhancements (Barnett 2006), optimising recovery processes is of paramount importance. In turn, this would allow athletes to compete and train altogether with potentially reduced fatigue, muscle soreness or even injury risks.

Depending on fatigue mechanisms, recovery of force production capacity may take from seconds to days. Bishop et al. (2008) defined three forms of recovery. Immediate recovery corresponds to recovery within rapid, time-proximal finite efforts (e.g., leg recovery between strides while walking). Short-term recovery is between sets. Training recovery takes place between successive work-outs or competitions.

Nowadays, athletes use a wide variety of strategies to accelerate short-term recovery and more particularly training recovery. Active recovery, massage, cryotherapy, water immersion, compression garments are examples of modalities often studied and reviewed (e.g., Cheung et al. 2003; Barnett 2006; Banfi et al. 2010; Cortis et al. 2010; Pournot et al. 2011). As compared with passive rest, applying one of these different modalities might enhance recovery (e.g., Gill et al. 2006) by various mechanisms, such as (a) increases in blood flow and therefore metabolic by-products removal (for example with active recovery; Toubekis et al. 2008), (b) decreases in vessels permeability that would reduce muscle damage markers' efflux (e.g., Eston and Peters (1999) using cold-water immersion) and also (c) neuro-mediator release like endorphin that may induce transient analgesia (for example with electrical stimulation; Cheng and Pomeranz 1980).

Among the possible active recovery modalities, many athletes use electrical stimulation (see manufacturers' websites such as Compex). However, limited evidence exists regarding its effects to improve recovery kinetic of most physiological variables (strength, neuromuscular parameters, etc.), to maintain athletic performance (vertical jump, sprints, etc.) or to reduce subjective rating of muscle soreness. Therefore, after a brief presentation of methodological aspects, this review will examine electrical stimulation effects on the recovery of strength production capacity and on the reduction of muscle soreness. Furthermore, in the literature these effects have been explored following various fatiguing exercises such as repeated contractions of a single muscle group (Grunovas et al. 2007; Vanderthommen et al. 2010) but also in specific field situations such as futsal games (Tessitore et al. 2008) or climbing (Heyman et al. 2009). Therefore, care was taken to differentiate these types of exercises in the present review.

Electrical stimulation: methodological considerations

Electrical stimulation involves series of stimuli delivered superficially using electrodes placed on the skin. It is a key component for many medical and sport applications, and is largely used for rehabilitation, training and recovery purposes. When applied for recovery purposes, a considerable heterogeneity exists regarding stimulation characteristics. The different stimulation forms include microcurrent electrical neuromuscular stimulation (MENS; e.g., Allen et al. 1999), high-volt pulsed current electrical stimulation (HVPC; e.g., Butterfield et al. 1997), monophasic high voltage stimulation (MHVS; e.g., McLoughlin et al. 2004) or the most frequently used transcutaneous electrical nerve stimulation (TENS; e.g., Denegar and Perrin 1992). Other stimulation forms are also applied (e.g., Lattier et al. 2004; Martin et al. 2004; Tessitore et al. 2008; Cortis et al. 2010) and are presented under the general term 'low-frequency electrical stimulation' (LFES) for the clarity of the present review. However, people often confound the terminology since the difference between these modalities is not so evident. Examples of stimulation characteristics are presented on Table 1.

When considering electrical stimulation for post-exercise recovery, two main effects are expected (Fig. 1). The first one, related to the increased muscle blood flow, is an acceleration of muscle metabolites removal. To that purpose, electrodes are generally applied over muscle motor points (e.g., Lattier et al. 2004). The second effect is the reduction of muscle pain through the stimulation analgesic effect. To that purpose, electrodes are often applied at the injured site (e.g., Butterfield et al. 1997) but also away from it, such as at acupoints (So et al. 2007) or even contralaterally (see DeSantana et al. 2008).

Depending on stimulation characteristics, electrical stimulation is believed to alter blood flow. Indeed, while TENS increases cutaneous blood flow (Cramp et al. 2000, 2002), LFES induces light muscle contractions responsible for a muscle pump effect and therefore an enhanced muscle blood flow. As suggested by Vanderthommen et al. (1997), this muscle blood flow increase might also result from vasoactive metabolites coming from muscular contractions. However, to obtain this effect, stimulation has to be adequately delivered. Indeed, some studies used "strong but comfortable" intensities during LFES (Lattier et al. 2004; Martin et al. 2004). However, an excessive intensity might lead to partial ischemia whereas insufficient intensity might be inadequate to significantly increase blood flow. In addition, authors have shown that electrical stimulation could be an effective mean to increase venous blood return to the heart and therefore cardiac output (Grunovas et al. 2007).

In addition to this increased blood flow, electrical stimulation might reduce long-lasting DOMS symptoms. Indeed, TENS is widely used in clinical settings for acute and chronic pain treatments (Rushton 2002). High-frequencies (50–100 Hz) are associated with low-intensity stimulations (sensory intensity that causes strong but comfortable sensation without muscle contractions) whereas low-frequencies (<10 Hz) are associated with high-intensity stimulations (motor intensity that produces visible and light muscle contractions). It produces a transient analgesia originating from various central and peripheral mechanisms attributed to stimulation parameters

Table 1 Examples of electrical stimulation characteristics used for recovery

	Current characteristics	Stimulation intensity	Electrode placement
Microcurrent electrical neuromuscular stimulation (MENS)			
Allen et al. (1999)	10 min at 30 Hz + 10 min at 0.3 Hz	Subsensory level (200 and 100 μA)	Muscle belly
High-volt pulsed current (HVPC)			
Butterfield et al. (1997)	30 min at 120 Hz (impulse duration = 40 μs)	Submotor – Sensory level (comfortable sensation)	Site of pain
Low-Frequency Transcutaneous electrical nerve stimulation (TENS)			
Craig et al. (1996)	20 min at 4 Hz (impulse duration = 200 μs)	Submotor – Sensory level (comfortable sensation)	Site of pain
High-Frequency Transcutaneous electrical nerve stimulation (TENS)			
Craig et al. (1996)	20 min at 110 Hz (impulse duration = 200 μs)	Submotor – Sensory level (comfortable sensation)	Site of pain
Monophasic high voltage stimulation (MHVS)			
McLoughlin et al. (2004)	30 min at 120 Hz (impulse duration = 100 μs)	Submotor – Sensory level (comfortable sensation)	Muscle belly
Low-Frequency Electrical Stimulation (LFES)			
Lattier et al. (2004)	20 min at 5 Hz (impulse duration = 250 μs)	Motor level (comfortable contractions)	Muscle motor point

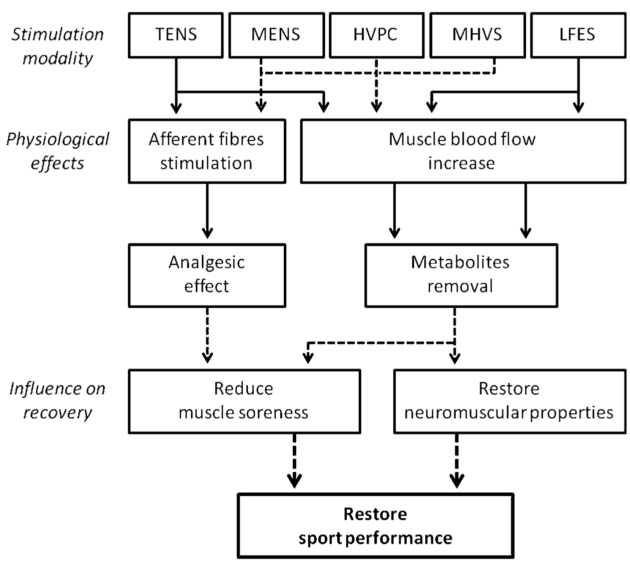

Fig. 1 Schematic view of known (*arrow*) and expected (*dashed arrow*) effects of different electrical stimulation forms used for post-exercise recovery. TENS: transcutaneous electrical nerve stimulation, *MENS* microcurrent electrical neuromuscular stimulation, *HVPC* high-volt pulsed current, *MHVS* monophasic high voltage stimulation, *LFES* low frequency electrical stimulation

(see DeSantana et al. 2008). High-frequency and low-intensity TENS has been shown to block the transmission of nociceptive afferent fibres in the spinal cord by stimulating large-diameter group II myelinated afferent fibres (Wall 1985). Low-frequency and high-intensity TENS is believed to stimulate group III and IV afferent fibres causing release of endogenous opioids in the central nervous system (Cox et al. 1993). According to DeSantana et al. (2008), high-frequency and high-intensity stimulation appeared to be the most effective TENS modality for pain treatment.

Electrical stimulation and recovery of neuromuscular parameters

Table 2 summarises some studies investigating electrical stimulation effects when used for recovery with different stimulation characteristics. In a recent study, Vanderthommen et al. (2010) examined the effects of LFES, active and passive recovery following three sets of 25 submaximal isometric knee extensions. Stimulation was administered at a low-frequency (5 Hz) associated with a motor intensity. No effect of the recovery mode was found for maximal torque production capacity. The absence of any effects was partly attributed to the "low aggressiveness" of the fatiguing exercise. To maximise fatigue, some authors used repetitive eccentric contractions but they did not observe any significant difference between electrical stimulation and passive recovery for immediate torque production capacity using either high-frequency TENS (Denegar and Perrin 1992) or LFES (Vanderthommen et al. 2007). Similarly, within a 7-day follow-up, LFES was not efficient to improve strength recovery kinetics (Vanderthommen et al. 2007). These different studies applied recovery treatments only once immediately after the fatiguing sessions. However, the repetition of electrical stimulation sessions within days following a fatiguing

Table 2 Main studies investigating recovery using electrical stimulation

Study	Recovery modalities	Fatiguing exercise	Outcomes	Effects
Denegar and Perrin (1992)	TENS (20 min) versus sham, cold, TENS + cold	Max. eccentric of elbow flexors	Strength	NS
			Muscle soreness	+
Butterfield et al. (1997)	HVPC (30 min) versus sham	30 × 10 submax. knee extensions	Strength	NS
			Muscle soreness	NS
Lattier et al. (2004)	LFES (20 min) versus PR and AR	10 min uphill running	Neuromuscular parameters	NS
Martin et al. (2004)	LFES (30 min) versus PR and AR	15 min one-legged downhill running	Neuromuscular parameters	NS
				NS
			Muscle soreness	
McLoughlin et al. (2004)	MHVS (30 min) versus PR	25 max. eccentric of elbow flexors	Strength	NS
			Muscle soreness	+
Grunovas et al. (2007)	LFES (10 min) versus PR	Submaximal ankle flexion	Muscle working capacity	+
				+
			Blood flow	
Tessitore et al. (2007)	LFES (20 min) versus PR and AR	100 min standardized soccer training	Vertical jump – Sprint	NS
			Subjective ratings	+
Vanderthommen et al. (2007)	LFES (25 min) versus PR	3 × 30 max. eccentric knee flexions	Isokinetic torque	NS
			Muscle soreness	NS
			CK activity	+
Tessitore et al. (2008)	LFES (20 min) versus PR and AR	30 min futsal game	Vertical jump – Sprint	NS
				NS
			Hormone	NS
			Subjective ratings	
Heyman et al. (2009)	LFES (20 min) versus PR, AR and WI	Climbing until exhaustion	Climbing test	NS
			Blood lactate	+
Neric et al. (2009)	LFES (20 min) versus PR and AR	200 yards frontcrawl swim	Blood lactate	+
Cortis et al. (2010)	LFES (20 min) versus PR, AR and WI	Submaximal running test	Vertical jump	NS
			Aerobic parameters	NS
			Subjective ratings	NS
Vanderthommen et al. (2010)	LFES (25 min) versus PR and AR	3 × 25 submax. isometric knee extensions	Isometric torque	NS
			Muscle soreness	NS

AR active recovery, *CK* creatine kinase, *HVPC* high-volt pulsed current, *LFES* low frequency electrical stimulation, *MHVS* monophasic high voltage stimulation, *PR* passive recovery, *TENS* transcutaneous electrical nerve stimulation, *WI* water immersion, *NS* non-significant electrical stimulation effect, + positive electrical stimulation effect

exercise does not appear more effective to accelerate recovery. This conclusion has been obtained using 30 min MHVS (high-frequency stimulations at sensory intensity) repeated eight times within 5 days after the fatiguing exercise (McLoughlin et al. 2004).

Neuromuscular properties have also been investigated following high-intensity intermittent running. In a first study, Lattier et al. (2004) tested the effectiveness of different recovery strategies, including LFES (motor intensity), after high-intensity intermittent uphill running. These authors concluded that the knee extensors neuromuscular properties, as attested by evoked contractile torque and electromyography, were not different after the various recovery modalities tested. In a second study, the same research team (Martin et al. 2004), investigated recovery time course using an intermittent but more strenuous exercise, i.e., 15 min one-legged downhill runs. Quite similarly, recovery time course (up to 4 days post-exercise) was similar with LFES as compared with active (submaximal running) and even passive recovery on knee extensors contractile properties (voluntary and evoked torque, voluntary activation). Thus, to date, whatever the muscular action mode, muscle group and stimulation parameters, electrical stimulation applied for recovery has been shown to be ineffective regarding torque production capacity and neuromuscular parameters (Table 2).

Electrical stimulation and recovery of athletic performance

The lack of any beneficial effect of electrical stimulation has also been observed during field situations in anaerobic conditions, such as vertical jumps and sprints (Tessitore et al. 2008), but also for aerobic variables such as oxygen consumption (Cortis et al. 2010) (Table 2).

Several studies have investigated the effects of electrical stimulation to evacuate muscle metabolic by-products during specific sport activities. Neric et al. (2009) compared the effects of passive, active (sub-maximal swimming) and LFES (motor intensity) recovery interventions following 200 yards frontcrawl sprint on blood lactate concentration. In this study, LFES was delivered on rectus femoris, latissimus dorsi and triceps brachii muscles. Results indicated that active recovery was the most efficient intervention to accelerate lactate removal. When compared with passive recovery, electrical stimulation also appeared useful for lactate removal but only at the end of the 20-min recovery period. Quite similar results have been obtained with active recovery and LFES following fatiguing climbing exercises (Heyman et al. 2009).

Beside enhanced blood flow (Grunovas et al. 2007) and lactate removal (Neric et al. 2009), the effects of LFES on subsequent athletic performance are not clear. Indeed, Lattier et al. (2004) tested the effectiveness of LFES after high-intensity intermittent uphill running designed to obtain metabolic fatigue. Although neuromuscular properties were not different after the various recovery modalities, these authors obtained, with LFES, a small trend toward a better performance during an all-out running test performed 80 min after the fatiguing running exercise. In opposition, compared with a first fatiguing bout, climbing performance was still impaired during a second bout after using LFES but returned to initial values immediately after active recovery (Heyman et al. 2009).

The lack of any measurable or consistent effects on muscle strength recovery and subsequent field performance could partly originate from methodological aspects. Indeed, as indicated previously, Martin et al. (2004) pointed out the necessity to apply an optimal stimulation intensity to maximise the muscle pump effect and therefore favour a possible positive recovery effect. Accordingly, Grunovas et al. (2007) recommended using stimulation intensity inducing 'fibrillation of individual muscle fibres rather than the muscle as a whole' to obtain an "electro-massage" and limit muscle ischemia.

According to these different studies, it appears that electrical stimulation, when used with low-frequency, might be a valid treatment for metabolites washout such as lactate (Neric et al. 2009). Beside this benefit, no study has been able to report any short-term effect and muscle recovery acceleration on neuromuscular, anaerobic and aerobic variables.

Electrical stimulation and recovery of muscle soreness

Practitioners widely use TENS currents for pain treatment. Hence, electrical stimulation has been applied to produce a transient analgesia and therefore diminish DOMS symptoms and muscle pain for example after fatiguing eccentric exercises. Conflicting results are however often reported. Craig et al. (1996) compared the effectiveness of high and low-frequency TENS on subjective pain scores. Although some lower pain scores were obtained with both TENS treatments, no statistical significant effect was noticed among the conditions (high and low frequency TENS vs. placebo and control). Contrarily, Denegar and Huff (1988) concluded that, independently of the frequency, TENS was a valuable technique for reducing muscle pain. For this parameter, high-frequency TENS appeared as effective as cold or cold combined with TENS when compared to control and placebo conditions (Denegar and Perrin 1992). These treatments also had positive effects for DOMS-associated joint range of motion recovery. However, pain reduction was not accompanied by a faster restoration of muscle strength.

The application of different current types (i.e., MENS, HVPC and MHVS) also revealed contradictory results. For example, no significant differences have been observed between MENS (0.3 Hz frequency and 30 μA intensity), massage and control conditions in minimising muscle soreness immediately and 24 h after exercise (Weber et al. 1994). This stimulation treatment, when applied immediately and several days after DOMS induction also appeared ineffective for reducing subjective pain scores or loss of elbow extension range of motion (Allen et al. 1999). In opposition, some authors concluded that this type of stimulation could induce a transient analgesia (Denegar et al. 1992) as pain was significantly reduced 24 and 48 h after the fatiguing exercise (repeated eccentric contractions of elbow flexors). Finally, HVPC has been shown to be as ineffective as MENS in reducing muscle pain (Butterfield et al. 1997) while McLoughlin et al. (2004) noticed that early and frequent application of MHVS transiently attenuates muscle soreness (Table 2).

LFES also conducts to conflicting results (Table 2). Nevertheless most studies noticed a lack of positive effects for subjective pain sensations after fatiguing isometric (Vanderthommen et al. 2010) or eccentric contractions (Vanderthommen et al. 2007), submaximal running (Cortis et al. 2010), futsal games (Tessitore et al. 2008) and one-legged downhill runs (Martin et al. 2004). In contradiction, one study registered lower muscle pain after soccer training using LFES and dry-aerobic exercises as compared with water-aerobic exercises and passive recovery (Tessitore et al. 2007).

These contradictory results might be due to the heterogeneity in fatiguing exercises inducing DOMS, subjects' characteristics and to the stimulation parameters adopted. The previously cited fatiguing exercises produced different muscle soreness levels. While Tessitore et al. (2007) induced only a light muscle pain (~2 on a 10-point pain scale), other studies induced severe soreness sensations (~6 on a 10-point pain scale for Vanderthommen et al. 2007). Concerning stimulation parameters, Wolcot et al. (1991) noticed that HVPC used with submotor stimulation intensity was more effective in reducing DOMS perception than subsensory HVPC and MENS.

Exercise-induced muscle damages have also been indirectly quantified using serum creatine kinase levels. Accordingly, three days after three sets of 30 maximal eccentric contractions of knee flexor muscles, Vanderthommen et al. (2007) noticed significantly lower creatine kinase activity using LFES (motor intensity) compared to passive recovery. No difference was obtained for initial muscle damage (1 and 2 days post-exercise). A similar result has previously been obtained using MENS (Rapaski et al. 1991). This reduced creatine kinase activity, indicating cellular debris washout, was attributed to the electro-induced muscle blood flow increase (Vanderthommen et al. 2007). A decreased inflammatory response could therefore be obtained. However, no comparison has been made with other recovery strategy and this aspect needs further investigation.

Concluding remarks

When used as a recovery modality, electrical stimulation demonstrated some positive effects on lactate removal or creatine kinase activity but evidence regarding performance indicators restoration, such as muscle strength, is still lacking. The absence of any positive effect could partly be attributed to methodological concerns such as the arbitrary choice of stimulation intensity. In addition, most positive electrical stimulation effects have been obtained on subjective parameters such as pain perception. This recovery strategy might therefore improve subjective feeling of well-being and could also aid athletes' attitude toward training (Tessitore et al. 2008). Indeed, as indicated in Cortis et al.'s (2010) study, most subjects cited electrical stimulation as the most effective intervention as compared with water exercises and sitting rest. Accordingly, although no effect was obtained for performance, electrical stimulation (applied alone or combined with another recovery modality) appeared to be a valid alternative treatment for post-exercise recovery when soreness is the most important limiting factor.

References

Allen JD, Mattacola CG, Perrin DH (1999) Effect of microcurrent stimulation on delayed-onset muscle soreness: a double-blind comparison. J Athl Train 34:334–337

Allen DG, Lamb GD, Westerblad H (2008) Skeletal muscle fatigue: cellular mechanisms. Physiol Rev 88:287–332

Ament W, Verkerke GJ (2009) Exercise and fatigue. Sports Med 39:389–422

Banfi G, Lombardi G, Colombini A, Melegati G (2010) Whole-body cryotherapy in athletes. Sports Med 40:509–517

Barnett A (2006) Using recovery modalities between training sessions in elite athletes. Does it help? Sports Med 36:781–196

Bishop PA, Jones E, Woods AK (2008) Recovery from training: a brief review. J Strength Cond Res 22:1015–1024

Butterfield DL, Draper DO, Ricard MD, Myrer JW, Durrant E, Schulthies SS (1997) The effects of high-volt pulsed current electrical stimulation on delayed-onset muscle soreness. J Athl Train 32:15–20

Cheng R, Pomeranz B (1980) Electroacupuncture analgesia could be mediated by at least two pain-relieving mechanisms: endorphin and non-endorphin systems. Life Sci 25:1957–1962

Cheung K, Hume PA, Maxwell L (2003) Delayed onset muscle soreness. Treatment strategies and performance factors. Sports Med 33:145–164

Cortis C, Tessitore A, D'Artibale E, Meeusen R, Capranica L (2010) Effects of post-exercise recovery interventions on physiological, psychological, and performance parameters. Int J Sports Med 31:327–335

Compex website. http://www.compex.info/en_UK/Who_uses_it_.html. Accessed 3 March 2011

Cox PD, Kramer JF, Hartsell H (1993) Effect of different TENS stimulus parameters on ulnar motor nerve conduction velocity. Am J Phys Med Rehab 72:294–300

Craig JA, Cunningham MB, Walsh DM, Baxter GD, Allen JM (1996) Lack of effect of transcutaneous electrical nerve stimulation upon experimentally induced delayed onset muscle soreness in humans. Pain 67:285–289

Cramp AFL, Gilsenan C, Lowe AS, Walsh DM (2000) The effect of high- and low-frequency transcutaneous electrical nerve stimulation upon blood flow and skin temperature in healthy subjects. Clin Physiol 20:150–157

Cramp AFL, McCullough GR, Lowe AS, Walsh DM (2002) Transcutaneous electric nerve stimulation: the effect of intensity on local and distal cutaneous blood flow and skin temperature in healthy subjects. Arch Phys Med Rehabil 83:5–9

Denegar CR, Huff CB (1988) High and low frequency TENS in the treatment of induced musculoskeletal pain: a comparison study. Athletic Train 23:235–237

Denegar CR, Perrin DH (1992) Effect of transcutaneous electrical nerve stimulation, cold, and a combination treatment on pain, decreased range of motion, and strength loss associated with delayed onset muscle soreness. J Athl Train 27:200–206

Denegar CR, Yoho AP, Borowicz AJ, Bifulco N (1992) The effects of low-volt microamperage stimulation on delayed onset muscle soreness. J Sport Rehab 1:95–102

DeSantana JM, Walsh DM, Vance C, Rakel BA, Sluka KA (2008) Effectiveness of transcutaneous electrical nerve stimulation for treatment of hyperalgesia and pain. Curr Rheumatol Rep 10:492–499

Eston R, Peters D (1999) Effects of cold-water immersion on the symptoms of exercise-induced muscle damage. J Sports Sci 17:231–238

Gandevia SC (2001) Spinal and supraspinal factors in human muscle fatigue. Physiol Rev 81:1725–1789

Gill ND, Beaven CM, Cook C (2006) Effectiveness of post-match recovery strategies in rugby players. Br J Sports Med 40:260–263

Grunovas A, Silinskas V, Poderys J, Trinkunas E (2007) Peripheral and systemic circulation after local dynamic exercise and recovery using passive foot movement and electrostimulation. J Sports Med Phys Fitness 47:335–343

Heyman E, De Geus B, Mertens I, Meeusen R (2009) Effects of four recovery methods on repeated maximal rock climbing performance. Med Sci Sports Exerc 41:1303–1310

Lattier G, Millet GY, Martin A, Martin V (2004) Fatigue and recovery after high-intensity exercise. Part II: Recovery interventions. Int J Sports Med 25:509–515

Martin V, Millet GY, Lattier G, Perrod L (2004) Effects of recovery modes after knee extensor muscles eccentric contractions. Med Sci Sports Exerc 36:1907–1915

McLoughlin TJ, Snyder AR, Brolinson PG, Pizza FX (2004) Sensory level electrical muscle stimulation: effect on markers of muscle injury. Br J Sports Med 38:725–729

Neric FB, Beam WC, Brown LE, Wiersma LD (2009) Comparison of swim recovery and muscle stimulation on lactate removal after sprint swimming. J Strength Cond Res 23:2560–2567

Pournot H, Bieuzen F, Duffield R, Lepretre PM, Cozzolino C, Hausswirth C (2011) Short term effects of various water immersions on recovery from exhaustive intermittent exercise. Eur J Appl Physiol. doi:10.1007/s00421-010-1754-6

Rapaski D, Isles S, Kulig K, Boyce D (1991) Microcurrent electrical stimulation: a comparison of two protocols in reducing delayed onset muscle soreness. Phys Ther 71:S116

Rushton DN (2002) Electrical stimulation in the treatment of pain. Disabil Rehabil 24:407–415

So RCH, Ng JKF, Ng GYF (2007) Effect of transcutaneous electrical acupoint stimulation on fatigue recovery of the quadriceps. Eur J Appl Physiol 100:693–700

Tessitore A, Meeusen R, Cortis C, Capranica L (2007) Effects of different recovery interventions on anaerobic performances following preseason soccer training. J Strength Cond Res 21:745–750

Tessitore A, Meeusen R, Pagano R, Benvenuti C, Tiberi M, Capranica L (2008) Effectiveness of active versus passive recovery strategies after futsal games. J Strength Cond Res 22:1402–1412

Toubekis AG, Tsolaki A, Smilios I, Douda HT, Kourtesis T, Tokmakidis SP (2008) Swimming performance after passive and active recovery of various durations. Int J Sports Physiol Perform 3:375–386

Vanderthommen M, Depresseux JC, Bauvir P, Degueldre C, Delfiore G, Peters JM, Sluse F, Crielaard JM (1997) A positron emission tomography study of voluntary and electrically contracted human quadriceps. Muscle Nerve 20:505–507

Vanderthommen M, Soltani K, Maquet D, Crielaard JM, Croisier JL (2007) Does neuromuscular electrical stimulation influence muscle recovery after maximal isokinetic exercise? Isokinetics Exerc Sci 15:143–149

Vanderthommen M, Makrof S, Demoulin C (2010) Comparison of active and electrostimulated recovery strategies after fatiguing exercise. J Sports Sci Med 9:164–169

Wall PD (1985) The discovery of transcutaneous electrical nerve stimulation. Physiotherapy 71:348–352

Weber MD, Servedio FJ, Woodall WR (1994) The effects of three modalities on delayed onset muscle soreness. J Orthop Sports Phys Ther 20:236–242

Wolcot C, Dubek D, Kulig K, Weiss M, Clark T (1991) A comparison of the effects of high volt and microcurrent stimulation on delayed onset muscle soreness. Phys Ther 71:S117