Neuromuscular electrical stimulation during recovery from exercise: a systematic review

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Neuromuscular electrical stimulation (NMES) during recovery from exercise: A systematic review

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ABSTRACT

The use of sub-tetanic low intensity neuromuscular electrical stimulation (NMES) for the purpose of promoting recovery from exercise has increased in recent years. The aim of this systematic review was to assess the effects of NMES on exercise recovery. A computerised database search of PubMed, CINAHL Plus, Sport Discus and Cochrane Library electronic databases was conducted for the time period Jan 1st 1970 to Mar 8th 2012. Only studies which used healthy uninjured humans and motor-threshold electrical stimulation compared to at least one other recovery modality for the purpose of promoting recovery from exercise were eligible for selection. Thirteen studies satisfied the inclusion criteria and were included for analysis (11 randomised crossover trials (RXT's), 1 randomised control trial (RCT) and 1 classified as other (OTH)). A quality assessment rating of the studies was performed using an extended version of The Cochrane Collaboration's Tool for Assessing Risk of Bias. Because of the heterogeneity of the study protocols, a qualitative review (best evidence synthesis) was performed for all outcomes, while the results for blood lactate (BLa) were also included in a meta-analysis. Eight studies were classified as high quality, 4 as medium quality, and one as low quality. Three studies found a positive outcome for a subjective measure of muscle pain, 3 for BLa, one for lowering creatine kinase, and only one for a performance parameter. The meta-analysis showed no evidence in favour of NMES vs. active (ACT) and mixed evidence vs. passive (PAS) recovery for BLa. In conclusion, whilst there may be some subjective benefits for post-exercise recovery, evidence is not convincing to support NMES for enhancing subsequent performance.

Key Words: Risk of bias, best evidence synthesis, meta-analysis, subjective ratings, blood lactate, performance parameters.

INTRODUCTION

In competitive sport, recovery from the fatigue induced during intense exercise bouts requires a time period of recovery, the duration of which, is dependant on the type and level of sporting activity and the trained status of the athlete. According to Bishop et al. (5), there are 3 forms of recovery: 1) immediate, which is the recovery between muscle contractions or movements; 2) short-term, which is the recovery between bouts of exercise; 3) training recovery, which is the recovery period required between successive sessions. Inadequate recovery of any of these forms, especially short-term and training recovery can negatively affect sports performance or increase the risk of injury (4). Since it is important for athletes to achieve adequate recovery, especially in elite level sport where the margins between winning and losing are often extremely small, the development of modalities aimed at enhancing the recovery process for athletes have been at the forefront of much of the scientific research into training methods and technology over the years. As athletes continually strive to acquire a competitive advantage over their competitors, many commercial companies have aligned themselves to this market by researching and developing new, or advancing existing recovery techniques and modalities for such sporting populations. This has resulted in the availability of a wide range of diverse recovery modalities for modern day athletes. Examples include cold and contrast water therapy, massage, low-level laser therapy, compression garments, hyperbaric oxygen therapy and neuromuscular electrical stimulation (NMES) (4).

Based on the plethora of previous investigations, it appears that NMES can be used effectively for increasing indices of both strength and power in athletic populations, without interfering excessively with sports specific training (19). In comparison, fewer studies have examined the effects of NMES as a recovery intervention to enhance sporting performance. When considering electrical stimulation for post-exercise recovery, the type of NMES

protocol used will normally be dictated by the type of recovery sought after. If the aim is to induce visible muscle contractions to increase muscle blood flow, and thus muscle metabolite removal, motor threshold electrical stimulation (NMES) with the electrodes positioned over the muscle motor points is normally used. Whereas, if the aim is to provide an analgesic effect on muscle soreness by blocking transmission of nociceptive afferent fibres, sub-motor stimulation (sensory level) is normally used (3).

When fatigue is induced following exercise, its effects can be either acute or chronic. Acute effects are for situations where complete recovery normally occurs within an hour or shortly thereafter. This is normally where high intensity exercise induces a short-term impairment resulting from metabolic disturbances that require sufficient time for a return to homeostatis (4). Motor threshold stimulation protocols that induce muscle blood flow, leading to a purported increase in metabolite removal from the exercised muscle, are normally used for these types of studies. Chronic effects are for situations where exercise normally induces considerable muscle damage and soreness, the effects of which can take up to 1 week to subside (9). These types of studies, where the emphasis is on a reduction in perceived muscle pain and an increase in muscle function over a longer period of time, more often use sensory level stimulation protocols. However, some studies have also used motor threshold protocols for these types of studies. Examples include Martin et al. (22), who investigated the effects of NMES on recovery from eccentric-contraction-induced injury over a 96-hr period and stimulated the subjects' knee extensors and planter flexors using a protocol frequency of 8 Hz, Pulse width 400 µs at 20-30 mA to achieve strong but comfortable visible contractions. A study by Vanderthommen et al. (32) induced delayed onset muscle soreness (D.O.M.S.) of the knee flexor muscles in 10 healthy subjects, and stimulated the subjects' hamstring muscle groups using a continuous protocol consisting of bi-directional symmetric rectangular

impulses at a pulse width of 250 μs and frequency of 5 Hz to achieve visible non-tetanic muscle contractions.

There have been numerous previous studies that have investigated the effects of various sensory level electrical stimulation protocols on sports recovery enhancement (2,7,11,12,24). Although these forms of electrical stimulation are normally used at sub-motor threshold, i.e., insufficient intensity to induce muscle contractions, they are purported to have potential positive effects on post-exercise muscle soreness and thus exercise recovery (3). For example, the use of high-volt pulsed current electrical stimulation (HVPC) has also been shown to be effective for managing the formation of edema after acute injury in animal studies (29). It has been suggested that this is achieved by: 1) Limiting micro-vascular permeability, thus minimising the leakage of plasma proteins from cell membranes into the interstitial fluid; 2) Repelling large negatively charged plasma proteins from the interstitial space by the placement of the negatively charged electrodes over the skin, which in turn increases the uptake of plasma proteins into the lymphatic channels (29). Regarding the previous studies outlined which investigated the use of sensory level electrical stimulation for enhancing sports recovery, despite being shown to decrease muscle soreness, the findings for enhancement on indices of sports performance have been less than convincing (3).

As described, there has been a significant body of research that has previously investigated the use of sensory level electrical stimulation for promoting exercise recovery. However, this systematic review only includes studies which used electrical muscle stimulation modalities that operated at motor threshold, i.e., induced visible muscle contractions. Because it is the sub-maximal contraction of skeletal musculature that provides the basis of an active recovery workout, this review investigated how NMES compared to other ‘active’ forms of recovery where muscle contractions were induced, as well as its effectiveness compared to the

traditional practice of passive recovery. Therefore, the aim of this review was to analyse previous research that investigated the effectiveness of using motor-threshold NMES compared to alternative methods, as a recovery intervention tool for enhancing recovery from exercise.

Many commercial manufacturers promote their NMES products as being effective for enhancing recovery using marketing techniques such as athlete testimonials, often with limited scientific evidence to support these claims. Therefore, the findings of this review should provide the following important information for scientists, athletes and coaches by providing an: 1) Overall consensus as to whether or not NMES can be considered an effective method for enhancing recovery compared to alternative modalities, in both healthy and athletic populations; 2) Analysis of the effectiveness of NMES for enhancing specific physiological and psychological outcome measures, such as its effects on subsequent exercise performance, muscle function recovery, blood markers and perceptions of pain; 3) Analysis of the type of NMES protocol designs which have been used to investigate recovery from exercise and how do they compare across studies with regard to: a) what ranges were used for NMES parameters such as pulse duration, frequency and intensity; b) what time periods were used for the NMES interventions and how long were the post intervention periods; 4) Analysis of potential limitations with protocol methodologies used, that could be perceived as introducing bias to the research conducted; 5) Exploration of any gaps that may be present in the existing literature that could pave the way for future research.

METHODS

Experimental Overview

This systematic review of the literature examined the effectiveness of motor-threshold electrical stimulation (NMES) as a recovering intervention from exercise bout(s) in healthy and athletic populations. The structure of this review involved three separate stages:

- **Stage One:** A literature search of the four databases (PubMed, CINAHL Plus, Sport Discus and Cochrane Library), using a combination of key words was conducted by the reviewer (J.M). An automated citation referencing system (Endnote X4.0.2) was used to manage and store all referenced studies.

- **Stage Two:** Two independent reviewers (J.M. and B.C.) screened the literature titles and abstracts in the database, before conducting a full reference list search of the selected articles to extract the relevant articles using the specified inclusion criteria (Table 1). A third independent reviewer (C.B.) was also used at designated stages throughout the selection process. Once a final decision had been made by consensus, the relevant articles were included for further analysis in this systematic review (Figure 1).

- **Stage Three:** A quality assessment tool (QAT) for rating the quality of the selected articles was developed using 'The Cochrane Collaboration's Tool for Assessing Risk of Bias' tool as a template, which was modified by the investigators to make it more specific and relevant for classifying the selected articles. The 2 independent reviewer's quality rated all 13 studies for risk of bias, and with the help of the third reviewer (C.B.), classified the selected articles by consensus according to their perceived risk of bias. Because of the considerable heterogeneity among the protocol design of studies, a qualitative review of the outcome measures were assessed (best evidence synthesis), with the exception of blood lactate (BLa) where a meta-analysis was also used.

Stage One: Literature Search

A Systematic search of PubMed, CINAHL Plus, Sport Discus and Cochrane Library electronic databases was conducted by the reviewer (J.M.). These databases were selected following advice from the Institutional Librarian when performing systematic searches of literature in the area of sports medicine, and specific keywords were inserted in combinations for each of the four databases.

Each specific keyword and phrase associated with electrical stimulation (EMS, NMES, Electrical Muscle Stimulation, Neuromuscular Electrical Stimulation, Electrical Stimulation, Electrical and Stimulation) was individually inputted in combination with each of the words ”Exercise”, “Sport”, “Recovery”, “DOMS” and “Delayed Onset Muscle Soreness” in all four of the specified databases. All articles extracted from the database search using the combination of keywords were exported to the automated citation referencing system. To reduce the likelihood of abstraction errors, the data extraction process: 1) set no ‘limits to search’, other than ‘Human Only’ and ‘English Language Only’, and 2) included duplicates, which were manually filtered by the reviewer (J.M.) once all extracted studies had been filed into the automated citation referencing system. Once all duplicates had been discarded, the total number of articles for review (n=4,939, Figure 1) was completed and ready for Stage Two of the process.

Stage Two: Literature Screening and Extraction of Data

The extraction process of the selected articles was done using the specified inclusion criteria outlined in Table 1. This process involved the screening of titles, abstracts and keywords of the selected articles by two independent reviewers (J.M. and B.C). Relevant review articles, which would not be used for final analysis, but would be used for subsequent reference list checks, were also included in this phase of screening. Once both reviewers had completed

their lists, a third independent reviewer (C.B.) screened both lists to extract the relevant studies using the inclusion criteria set out in Table 1. Upon collaboration between the three reviewers (J.M., B.C. and C.B.), after an initial 88% agreement where a total of 16 articles were selected between reviewers (12 original articles and 4 review articles for reference list searches), an 100% agreement was achieved when consensus was reached and the number of articles forwarded was 14 (10 original articles and 4 review articles) for the next phase of screening, as shown in Figure 1.

The two independent reviewers (J.M. and B.C.) then screened the reference lists of the selected articles. Although the screening of reference lists included the selected articles and review articles extracted from the previous phase of screening, it also included other articles (*n*=11, Figure 1) which were deemed potentially relevant but were not contained within the database search list. These articles included such review articles as 'Recovery Modalities for Sport', which were not specific to NMES, but covered a wide range of recovery modalities including NMES, but may not have included the term in the title, abstract or keywords. Once both reviewers (J.M. and B.C.) had completed their lists, using the same inclusion criteria, the third independent reviewer (C.B.) again screened both lists to extract the relevant studies using the same inclusion criteria, exactly as done previously. As before, after collaboration between the three reviewers (J.M., B.C. and C.B.), the final number of articles added to the list was agreed upon by consensus. After initially including a total of 6 articles between reviewers, a 100% agreement was achieved when consensus was reached and 3 of these 6 articles were added. Therefore, the final number of articles forwarded for the next phase of screening was 13 (Figure 1). Once a final decision had been made, the relevant studies were included for further analysis in Stage Three of this systematic review.

Stage Three: Data Analysis, Quality Rating Assessment & Meta-Analysis

This stage commenced once the relevant articles had been selected during Stage Two. The findings of all 13 articles are summarised in Table 2.

Data Analysis

Prior to the quality assessment, the selected articles were grouped together (Table 3) for analysis of the following: 1) **Demographics:** sample size, gender, age, height, body-mass and trained status; 2) **Time Periods:** how long the recovery intervention modalities were administered for, and how long the total recovery period of each study was; 3) **Interventions:** how many interventions (other than NMES) were involved in each study, the studies which included at least one PAS, and/or at least one ACT, and/or any other recovery modality other than PAS or ACT; 4) **NMES Parameters:** the average frequency, pulse durations (widths) and average intensity stimulation parameters used during each study protocol (average frequencies and intensities were used as these changed during the recovery intervention period in some of the studies); 5) **Outcome Measures:** the studies that used a post-intervention exercise bout, studies that included BLa analysis, or at least one performance measure outcome or at least one subjective rating of muscle soreness outcome measure.

The above data for all studies were pooled together as shown in Table 3. However, because of the considerable heterogeneity that exists among study protocol designs, a meta-analysis of the data was not conducted for the majority of outcome measures (except BLa), as it is deemed inappropriate by the Cochrane Collaboration in these circumstances (16). However, a qualitative review was performed (best evidence synthesis) for the following categories: BLa, performance parameters, perceptions of pain ratings, and perceptions of exertion ratings. These categories were rated using a ratings system of four levels of evidence, a

process which has been used previously where a meta-analysis was not deemed appropriate (34).

- **Level 1 – Strong Evidence:** where there are consistent findings in multiple high quality (low risk of bias) studies.

- **Level 2 – Moderate Evidence:** where there are consistent findings in at least one high quality study and one or more medium quality (unclear risk of bias) studies.

- **Level 3 – Limited or Conflicting Evidence:** where there is only one finding in either a high or medium quality study or inconsistent findings in medium or low quality (high risk of bias) studies.

- **Level 4 – No Evidence:** where there is only one finding in a medium quality study or inconsistent findings in low quality studies.

Quality Assessment Tool (QTA)

Studies were classified as randomized control trials (RCT's) if they used 2 or more separate study groups who were randomly allocated to their groups (25). Studies were classified as randomized cross-over controlled trials (RXT's) if participants underwent 2 or more recovery interventions in a random order separated by a washout period, with each participant acting as his/ her own control to permit between and within group comparisons (25). Studies were classified as OTH if they were another study design other than a RCT or a RXT. Not surprisingly the majority of the selected studies used a RXT protocol design, especially as these are the most appropriate types used where the effects are short lived and reversible (25).

The selection of a suitable Quality Assessment Tool (QAT) for the rating of the selected studies, particularly for RXT's, proved difficult, which is often a problem associated with

rating RXT's (25). The use of QAT's such as the Physiotherapy Evidence Database Scale (PEDRO) or the Effective Public Health Practise Project Quality Assessment Tool (EPHPP), whilst valid and reliable QAT's, did not work particularly well for rating the selected studies. That is, because the design of the tools are not particularly well suited for rating RXT's, when trialled using the selected studies (the majority of which are RXT's), the scoring was very often similar between studies despite obvious differences in quality present which were not detected. Therefore, some of the better quality studies were being classified similar to some of the lesser quality studies.

Because of the problems mentioned above, it was decided to use the 'Cochrane Collaboration's Tool for Assessing Risk of Bias' as a template for the QAT used to rate the selected studies. Whilst this template is designed more specifically for RCT's, it does allow the addition of extra sub-sections to this template under the section 'Other Sources of Bias'. Therefore, a series of relevant quality assessment questions, aimed specifically to address concerns relevant to these types of studies were incorporated into this Table, with additions shown in italics (Table 4). The 2 independent reviewers (J.M. and B.C.) used this edited table as the QAT to rate the selected studies. Upon completion, the third reviewer (C.B.) assessed the findings. Upon collaboration between the three reviewers (J.M., B.C. and C.B.), the final rating of each study was agreed upon after an initial 85% agreement (11 of 13) between reviewers, a 100% agreement was achieved when a consensus was reached. The studies were classified into three categories, as shown below and in Table 5, which is a modification of the model used by vanTulder et al. (34) where they classified a study as high quality if it fulfilled $\geq$ 5 of 9 of their validity criteria. Using this as a guide, the authors classified, by consensus, the studies according to how they fulfilled each of the 10 criteria:

- **'+': Low Risk of Bias (High Quality):** studies were deemed a low risk of bias if they were classified as low risk (+) in at least 6 and not classified as high risk in any of the 10 individual categories .

- **'?': Unclear Risk of Bias (Medium Quality):** studies were deemed an unclear risk of bias if were classified as low risk (+) in between 4 and 6 and as high risk in at least 1 of the 10 individual categories.

- **'-': High Risk of Bias (Low Quality):** studies were deemed a high risk of bias if they were classified as low risk (+) in less than 3 and a high risk in at least 1 of the 10 individual categories.

RESULTS

Data Analysis

Demographic: Across the 13 studies analysed, 189 subjects were included in total, of which: 137 (72.5%) were males; 40 (21.2%) were females; and 12 (6.3%) were unknown, as their gender was not stated. Males were included in 11 of the 13 studies, including 2 studies where mixed gender groups were used. Females were included in only 3 of the 13 studies, including the 2 studies where mixed gender groups were used. There were 11 studies classified as RXT's, with 1 study using a RCT and the remaining one classified as OTH. The mean sample size used among the 13 studies was n=14±7 (Min/Max: 7/30). Of the 11 studies that used a RXT, the mean sample size used was n=13±7 (Min/Max: 7/30). One study (8) employed a RCT, using 3 separate groups each containing 8 participants. The remaining study (36), who performed two individual studies (Studies 1 and 2) as part of their study, used a separate group of different subjects for each study, with sample sizes of 14 and 13 for studies 1 and 2 respectively.

Subjects' mean age was stated in all studies. The mean age from all study populations pooled together was 26.1±8.8 yr (Min/Max: 17.7/47.3 yr). Subjects' mean height was stated in 10 of the 13 studies. The mean height from all study populations pooled together was 176.1±3.9 cm (Min/Max: 168.9/182.8 cm). Subjects' body mass (BM) was stated in all studies. The mean BM from all study populations pooled together was 72.0±6.9 kg (Min/Max: 55.4/84.9 kg). The training status of subjects was stated in all studies. Of these, 9 studies used subject populations classified as trained, whilst 4 studies used subject populations classified as non-trained or habitually active.

Recovery Times: The duration of time that the recovery intervention modalities were used subsequent to the pre-intervention bouts of exercise were stated in all studies. The mean time of the recovery intervention periods of all studies pooled together was 27±15 min (Min/Max: 6/60 min). The total recovery period duration used by studies was stated in all studies. The mean time of the total recovery periods of all studies pooled together was 26.8±48.0 hr (Min/Max: < 0.1/168 hr).

Interventions Used: Of the 13 studies (including NMES in each case), 2 studies used 2 different recovery intervention modalities, 8 studies used 3 different recovery intervention modalities and 3 studies used 4 different recovery intervention modalities. Of these, all used PAS recovery as one of their recovery intervention modalities, 10 used ACT recovery and 4 used another form of recovery intervention (massage, cold water immersion (CWI), and water exercises). Descriptions on interventions applied in studies can be viewed in Table 2.

NMES Parameters: The impulse frequency parameters used during NMES was stated in all studies. However, in some studies, the frequency output changed throughout the recovery intervention period. Therefore, the mean impulse frequency results from all studies are reported as average frequencies used (AVG_{FREQ}), which was 4.7±2.4 Hz (Min/Max: 1.0/8.0

Hz). Pulse duration was stated in 10 of the 13 studies. The mean pulse durations used in these studies was 320±105 μs (Min/Max: 125/500 μs). The intensity of stimulation was only reported in 8 of the 13 studies. However, in some studies a range instead of specific details were given. Therefore, the mean intensity results from the 8 studies are reported as average intensities used (AVG_{INT}), which was 36±23 mA (Min/Max: 17.5 – 92 mA).

Outcome Measures: Of the 13 studies, only 6 used a post-recovery bout of exercise (Ex 2) to assess the effects on subsequent performance of each of the recovery interventions used. The remaining 7 studies used a form of outcome measure(s) which did not involve the use of an Ex 2. The outcome measures analysed were broadly classified into 3 separate categories: Blood Lactate (BLa), Performance Parameters (Perf), and Ratings of Measurements of Pain (Rating). Regarding these 3 outcome measures, only 3 studies investigated outcome measures from all 3 categories, whilst 7 of the 13 studies investigated outcome measures from 2 of the 3 categories. The remaining 3 studies only investigated from 1 of the 3 outcome measures. Of these, two studies (8,27) only analysed BLa for their outcome measures, whilst 1 study (17) only investigated performance parameters. In all, 6 of the 13 studies used BLa, 11 of the 13 studies used performance parameters and 9 of the 13 studies used ratings of measurements of pain as one of their outcome measures. Outcome measures data from all studies can be viewed in Table 3.

Quality Assessment Analysis

The QAT rating of all studies were agreed upon consensus from the 3 independent reviewers (J.M., B.C. and C.B.). Of the 13 studies, 8 were classified as having a low risk of bias (high quality), 4 were classified as have an unclear risk of bias (medium quality) and 1 was classified as having a high risk of bias (low quality), as shown in Table 5.

From the 6 studies who investigated the BLa lowering effects of NMES, 4 of these studies found a benefit of using NMES on lowering BLa compared to at least one other recovery intervention. Of these studies, 2 were rated as having a low risk of bias and 2 were rated as having an unclear risk of bias. From the 11 studies who investigated at least one performance parameter, 2 studies found a benefit of using NMES on performance compared to at least one other recovery intervention. Of these studies, 1 was rated as having a high risk of bias and 1 was rated as having an unclear risk of bias. From the 10 studies who investigated at least one rating of muscle pain or exertion, 4 studies found a benefit of using NMES on ratings of muscle pain or exertion compared to at least one other recovery intervention. Of these studies, 2 were rated as having a low risk of bias, 1 was rated as having an unclear risk of bias and 1 was rated as having a high risk of bias.

Level of Evidence & Meta-Analysis

As discussed, because of the considerable heterogeneity among study protocols, the level of evidence (best evidence synthesis) for the effects of the various recovery modalities on the following three outcome measures were used instead of a meta-analysis, with the exception of BLa which was analysed by both methods.

Blood Lactate: During a meta-analysis there is no general consensus about whether to use fixed or random effects model to assess heterogeneity (18). However, the Cochrane Handbook of Systematic Reviews (16) suggests that where statistical heterogeneity between studies is absent, the fixed effects model should be reported; while in the case of statistical heterogeneity, both random and fixed effects models should be computed and the more conservative of these reported. In the current case, random effects models emerged as the more conservative where heterogeneity existed and are thus reported in Tables 6 and 7 for selected comparisons. Therefore, both random and fixed effects models were computed to assess NMES vs. PAS and NMES vs. ACT recovery for BLa at designated times points,

386 as in the absence of between study heterogeneity, both fixed and random effects will provide the same
387 result (16).

388 For NMES vs. PAS (Table 6), at 10 min there was no heterogeneity in results between studies, I^2=
389 0%, with the overall pooled effect (*n*=56) in favour of NMES, although not statistically significant
390 (*P*=0.07). At 15 min, there was 'considerable' heterogeneity (I^2=85%) (according to Cochrane, an I^2
391 > 75% is considered 'considerable' (16)), with the overall pooled effect (*n*=37) in favour of NMES,
392 although not statistically significant (*P*=0.22). At 20 min there was no heterogeneity in results
393 between studies, I^2= 0%, with the overall pooled effect (*n*=43) statistically in favour of NMES
394 (*P*=0.007). At 25 and 30 min (no meta-analysis were performed as only one study used in each),
395 results significantly favour NMES at 25 min (P<0.00001), but not at 30 min (*P*=0.87).

396 For NMES vs. ACT (Table 7), at 10 min there was no heterogeneity in results between studies, I^2=
397 0%, with the overall pooled effect (*n*=56) statistically in favour of ACT (*P*=0.0006). At 15 min, there
398 was 'considerable' heterogeneity (I^2=90%), with the overall pooled effect (*n*=37) in favour of ACT,
399 although not statistically significant (*P*=0.26). At 20 min there was 'considerable' heterogeneity
400 (I^2=84%), with the overall pooled effect (*n*=43) statistically in favour of ACT (*P*=0.009). At 25 and
401 30 min (no meta-analysis were performed as only one study used in each), results significantly favour
402 ACT at 30 min (P<0.00001), but not at 25 min (*P*=0.40).

403 BLa was investigated during the recovery intervention period in 6 of the 13 studies. Of these,
404 4 were classified as high quality (10,15,21,27) and 2 as medium quality (8,35). When NMES
405 was compared to PAS recovery, 4 of the 6 studies showed that NMES had a significant BLa
406 lowering effect compared to PAS recovery (2 were classified as high quality studies (15,27)
407 and 2 as medium quality studies (8,35)). Only two studies (10,21), found no significant BLa
408 lowering effects of NMES compared to PAS recovery. Based on these and the results of the
409 meta-analysis for NMES vs. PAS and ACT recovery, there is strong evidence (Level 1) that
410 NMES is effective for lowering post exercise BLa compared to PAS recovery. When NMES
411 was compared to ACT recovery, only 1 medium quality study (35) showed that NMES had a

significant BLa lowering effect compared to ACT recovery. Whereas, 3 high quality studies (15,21,27) found that ACT recovery had a significant BLa lowering effect compared to NMES. One high quality (10), found no significant BLa lowering effects between NMES and ACT recovery. Therefore, there is no evidence (Level 4) that NMES is effective for lowering post exercise BLa compared to ACT recovery.

Performance Parameters: Performance parameters were investigated in 11 of the 13 studies. Of these, 7 were classified as high quality (10,15,17,21,22,30,32), 3 as medium quality (31,33,35) and 1 as low quality (36). When NMES was compared to PAS recovery, only 1 low quality study (36) showed that NMES had a significant positive effect on performance parameters compared to PAS recovery. There were no significant differences for performance parameters found for NMES compared to PAS recovery for all of the other 10 studies. Therefore, there is no evidence (Level 4) that NMES is effective for enhancing performance compared to PAS recovery.

When NMES was compared to ACT recovery, only 1 medium quality study (35) showed that NMES had a significant positive effect on performance parameters compared to ACT recovery. There was 1 high quality study (15) which showed that NMES had a significant negative effect on performance parameters compared to ACT recovery. There were no significant differences for performance parameters found for NMES compared to ACT recovery for all of the other 8 studies (one study (36) did not use an ACT recovery intervention). Therefore, there is weak evidence (Level 3) that NMES is ineffective for enhancing performance compared to ACT recovery.

Measurements of Perceptions of Pain or Exertion (Ratings): Ratings of perceptions of pain and/or perceptions of exertion were investigated in 9 of the 13 studies. Of these, 5 were classified as high quality (10,15,22,30,32), 3 as medium quality (31,33,35), and 1 as low

quality (36). When NMES was compared to PAS recovery, 4 studies showed that NMES had a significant positive effect on ratings of pain and/or exertion compared to PAS recovery. Of these, 2 were classified as high quality (10,30), 1 as medium quality (31), and 1 as low quality (36). There were no significant differences for ratings of pain or exertion for all of the other 5 studies. Therefore, there is strong evidence (Level 1) that NMES is effective for enhancing ratings of pain or exertion performance compared to PAS recovery. When NMES was compared to ACT recovery, only 1 medium quality study (35) showed that NMES had a significant positive effect on ratings of pain or exertion compared to ACT recovery. There was 1 high quality study (22) which showed that NMES had a significant negative effect on ratings of pain and/or exertion compared to ACT recovery. There were no significant differences for ratings of pain and/or exertion for all of the other 7 studies. Therefore, there is no evidence (Level 4) that NMES is any more effective than ACT recovery for improving perceptions of pain or improving perceptions of exercise exertion, either during or after a recovery intervention period.

DISCUSSION

The overall findings of this systematic review of previous studies which have investigated the use of NMES for the purpose of enhancing post exercise recovery, suggest that NMES in not more effective than traditional recovery intervention modalities for enhancing subsequent performance parameters. However, caution should be exercised when interpreting these findings, due to the heterogeneity that exists among study protocols, NMES parameters used and the quality rating of some of the important protocol procedures. From the 13 studies that were included for analysis, quality assessment rating revealed that whilst some were rated strongly, others were only rated medium (unclear risk of bias) or weak, particularly with

regards to reporting of protocol details and investigator bias. Also, some studies that showed overall positive results were either poorly controlled or assessed few outcomes.

The majority of studies analysed in this review used RXT's, which as previously stated are the most appropriate for these types of studies, especially if sample sizes are small. The procurement of a suitable QAT for these studies proved very challenging, which was not that surprising considering that the acquiring of a suitable QAT for rating RXT's can often be problematic, especially as there is a large heterogeneity in the reporting of RXT's, possibly reflecting the lack of standards with the field (25). It was decided that a revised version of 'The Cochrane Collaboration's Tool for Assessing Risk of Bias' would be more suitable for these studies, especially as the design of this tool allowed scope for modification of the tool to make it more specific to these type of RXT studies. This strategy, recommended by Moher et al. (26), has been adopted by previous researchers who have conducted systematic reviews (6,14,23).

Overall Findings

Regarding the overall findings of the 13 studies, 9 found a positive effect for NMES for at least one of the outcome variables measured. However, of these 9 studies, a positive effect for a performance parameter outcome measure was only found in only 2 studies (35,36), one of which was rated by the investigators as having a high risk of bias (weak quality rating), with the other study rating as an unclear risk (medium quality) due to several fundamental protocol issues found.

Four of the 9 mentioned studies (8,15,27,35) found that NMES had a positive BLa lowing effect during the recovery intervention period compared to PAS recovery. Although the results of the meta-analysis showed that there were heterogeneity between studies and while

there was a consistent trend for NMES to be associated with lower Bla vs. PAS, the sample sizes were small and the only significant effects were seen at 20 min. Also, two of the aforementioned studies (8,27) did not perform a post intervention exercise bout to assess its effects on subsequent performance. This could raise a question over these results, especially as lowering BLa alone may not result in a subsequent performance enhancement. This is because, despite traditional viewpoints to the contrary, lactate is no longer viewed as a major contributor to muscle fatigue (1). In support of this view, one study (15) showed that, despite BLa decreasing significantly faster during the recovery intervention period with NMES compared to PAS recovery, there were no significant performance differences between both groups for the post-recovery intervention exercise bout.

Four of the 9 mentioned studies (10,30,31,35), found a benefit on subjective ratings of muscle pain, yet only one of these studies (35), showed a direct performance benefit as a result. One study (33), found that NMES significantly lowered CK blood levels at 72 hr post eccentrically damaging exercise compared to PAS Recovery. However there were no significant differences for either performance parameters or ratings of muscle pain at any of the post exercise time points in their study.

The findings for subsequent performance parameters are very significant, especially as performance enhancement is likely the most important factor considered when using recovery intervention modalities, particularly for sporting populations. Yet only two studies (35,36) found any performance benefit of using NMES, both of which had potential protocol limitations (Table 5) resulting in being classified as having medium and high risk of bias respectively. The positive findings for ratings of muscle soreness in the three aforementioned studies are somewhat more encouraging, as although in most cases there were no significant

positive effects on performance parameters measured, the perceived benefit of positive psychological effects on recovery should not be dismissed (10).

NMES Parameters

A major observation with these studies is the considerable heterogeneity that exists between the study protocols, particularly for NMES parameters (Table 3). Regarding the NMES parameters, this is not that surprising as there is still no definitive consensus on what are the optimal parameters that should be used with NMES for post exercise recovery (28). The large variation of different NMES devices that are employed by investigators is likely a significant factor for this heterogeneity, especially in relation to variables such as electrode size and shape, pulse intensity and shape and pulse frequency.

Pulse Frequency: The mean frequency used by these studies was 4.7 Hz, with a range from 1 – 8 Hz. These are within the expected range of frequencies that are normally used for inducing sub-tetanic muscle contractions. NMES used for the purpose of enhancing post-exercise recovery is characterised by the use of low frequency, (relatively) high intensity stimulation to induce light muscle contractions, as opposed to high frequency low intensity that is normally used for sensory level stimulation (3).

Pulse Duration (Width): The mean pulse duration used by studies was 320μs, with a range from 125 – 500μs. Three of the studies (15,27,36) did not report pulse durations used. The general consensus on the optimal pulse durations that should be used for the purpose of exercise recovery is not definitive, but as shown from previous research, is normally between 100 – 500μs. It is believed that if the pulse duration is too narrow, it can result in insufficient muscle activation due to a minimum time required for the swell intensity to create an action potential within the stimulated motor neurons (13). Alternatively, if the pulse duration is too

wide, the proportionately deeper and more intensive muscle stimulation can be accompanied by undue discomfort due to the increased presence of algesic substances as the pulse duration rises (13). Overall, it is probably very difficult to recommend a specific range at which pulses durations should be fixed for recovery intervention protocols. This is likely due to the considerable heterogeneity that exists between NMES devices (such as electrode size, positioning) and parameters used between different studies which accounts for a lack of consensus.

Pulse Intensity: Only 9 of the 13 studies provided details about the intensity of stimulation used, although specific details were not entirely clear in all 9 studies. For example, one of the studies (27) stated that their NMES device was capable of achieving a maximum output intensity of 35 mA. They did not specifically state the range of values that all of their subjects used, instead stating that the intensity was 'typically' increased to an intensity of 7 – 10 to elicit a strong comfortable contraction, with 10 being the highest setting (35 mA) on a scale of 1 – 10. One of the studies (36) did not disclose any information on the intensity of stimulation, only that it was used at 'moderate intensity'.

Despite intensity of stimulation arguably being the most important NMES parameter (20), there is currently no consensus on what is the optimal intensity that should be used with NMES, when used during recovery from exercise. This present position is not helped by the fact that: 1) there is considerable heterogeneity that exists between study protocols with regard to NMES devices (electrode size and positioning) and parameters used; 2) There are large inter-individual differences into how people respond to NMES, which makes it very difficult to use similar NMES intensities for everybody. As previously mentioned the reasons for this heterogeneity are multi-variant and likely include factors such as individual perceptions of discomfort and levels of subcutaneous adipose tissue (19). Therefore, it is

very difficult to definitively state what the optimal intensity of stimulation for the post-exercise recovery should be. However, it is known that the higher the intensity of stimulation, the greater the number of motor units that will be activated and the deeper the level of muscle contraction attained. Therefore, it is likely that an increased intensity of stimulation will result in a greater muscle pump effect due to greater muscle activation, which in turn should increase muscle metabolite removal at a faster rate. However, because of the associated problems of increasing intensity, such as perceptions of discomfort and muscle fatigue, a balance clearly needs to be found between increasing muscle activation and reducing the likelihood of increasing muscle fatigue.

QAT Study Ratings

The 13 studies were rated for quality assessment to assess whether they were considered to be of high, medium or low quality, i.e., having a low, unclear or high risk of bias associated with the study protocol (Table 5). Each study was rated using a modified QAT which was designed to be specific to these types of controlled studies.

Random Allocation: Although the vast majority of studies stated that they used a random allocation to determine the order of the recovery intervention modalities, none of these studies reported their method of random allocation used. This absence of detail makes it unclear if there were any risk of bias associated with their respective randomisation procedures, which is why details about the method of sequence generation is recommended (16). Also, two of the studies either did not randomise or were confusing as to whether randomisation was used. Although one of these (36) only performed one recovery intervention session for each of their studies, in their protocol design, they did not randomize which leg received the NMES treatment. That is, in all cases, the right leg received NMES and left leg received PAS recovery. Another possible consideration with their design

protocol, apart from the issue of randomization, may be that systemic factors make it more difficult to assess the direct effects of NMES on the stimulated limb, especially as direct systemic blood flow to and from the limb during stimulation was not controlled. That is, because as suggested by the authors, NMES can exert systemic as well as peripheral effects, the use of NMES on one limb and not the other would not only directly effect the stimulated limb, but also effect systemic blood flow as a whole, which could carry over into the opposite leg, thus confounding results. The other study (35) did not appear to use a randomized process to select the order of their recovery intervention. However, they did not make it definitively clear whether they used a randomization process.

Regarding blinding procedures for the recovery intervention protocols used, no study implemented an NMES sham for any of their interventions. This does provide a limitation to studies and must be considered when interpreting results found. However, it is important to recognise that implementing an effective sham NMES intervention for studies of this nature would likely be difficult.

Familiarization Sessions: With regard to participant familiarization sessions prior to the implementation of the recovery intervention protocols, only 3 of the studies had implemented a familiarization session prior to the first recovery intervention session. However it must be noted that for 4 of the other studies that did not implement a familiarization session (27,30,31,35), they all used highly trained athletes performing exercises which were very familiar and specific to their everyday activities. This should make it far less likely that familiarization effects could interfere with the data collection, compared to, e.g., if they were un-trained populations or performing unfamiliar exercises to them. The implementation of a familiarization session was not applicable to 2 of the studies (22,33), as they used non-trained

603 populations who performed exercise protocols which were designed to induce muscle
604 soreness.

605 *Washout Periods:* The use of a washout period was not applicable to the two studies which
606 only had one testing session (8,36). Most of the other studies clearly reported the washout
607 periods between sessions, which appeared to be adequate in almost all cases. One study (27)
608 reported that the "3 sessions were separated by a minimum of 24 hr and were all completed in
609 within 3 weeks". The use of 24 hr, although quite short to allow full recovery from high
610 intensity exercise, was probably adequate in this case as: 1) they were using trained
611 swimmers performing a familiar exercise without a large eccentric component, and 2) the
612 only outcome measure was blood lactate, which returns to resting levels within 90 min after
613 very intensity exercise.

614 *Study Populations:* In general the populations used for the studies were appropriate for their
615 respective research protocols. That is, most of the studies used trained sports specific
616 populations who were performing exercise bout(s) and recovery intervention periods very
617 relevant to their sporting discipline. Therefore, these populations were generally very
618 representative of the type of sporting populations which were being targeted. Also because
619 they were specifically trained for the exercises being performed, this would likely
620 dramatically decrease the likelihood of a familiarization effects or inadequate washout
621 period(s) affecting the data recorded. Conversely, of the studies that used non-trained
622 populations, the aim of their studies were to induce muscle soreness and damage which made
623 these populations better suited for these situations than using trained athletic populations, as
624 they were unaccustomed to the exercises undertaken. However, despite the appropriateness
625 of the populations used for these studies, only 7 of the 12 studies adequately reported the

recruitment procedures, which meant that the other studies were at a higher risk of selection bias.

Pre-Intervention Exercise: The pre-intervention exercises chosen to induce fatigue were generally appropriate and well controlled, both in terms of their intensity and duration. However, there were some studies that used questionable exercise protocols. One such study (31) was generally a well conducted study. However, despite using a very appropriate specific population for their study, they used a Futsal match as their pre-intervention exercise. Because of the nature of such an exercise session, it would have been extremely difficult to standardise the level of fatigue induced by the sessions. This is because of the lack of control over exercise variables such as exercise intensity and durations of times spent walking, jogging sprinting and moving in multiple movement planes. Therefore, this makes it very difficult to determine to what extent the subsequent recovery intervention modalities affected the outcome measures, especially if the pre-intervention exercise sessions were not strictly controlled for all major variables between the multiple testing days.

Another study (36) used a pre-intervention exercise bout in their second study of hiking single or multiple loops of a course in a hill range, depending on subject fitness level. However, the trained status of subjects was not stated in their study methodology. They also did not control the post exercise bout period prior to the implementation of the recovery intervention modality, as they stated that “participants drove back to the centre, which took approximately 10 min”. Although, there was only one session involved, which meant controlling the variables for subsequent sessions was not an issue, because the protocol procedures were poorly controlled, such practises would likely increase the likelihood of bias occurring.

Recovery Interventions: The recovery intervention protocols were adequately detailed in almost all of the studies, with the majority of the studies implementing the modalities for 20 – 25 min. One of the studies (36) implemented their NMES protocol for a considerable longer duration than the other studies (60 min) for both parts of their study. However, they gave virtually no details about parameters used, which makes it very difficult to assess its appropriateness.

Statistical Analysis: Statistical analyses were appropriate and well reported for the majority of the studies, with one notable exception (36), who disclosed very little detail regarding their statistical analysis. Because none of the studies stated whether they had performed a power calculation to determine sample size needed, it was assumed that they did not perform one. The use of power calculations to estimate sample sizes are recommended when designing research protocols, especially as it decreases the chance of obtaining an underpowered result. However where statistically significant differences are found between groups in a trial, then the power and sample size are by definition adequate even if there was no a priori sample size calculation done.

PRACTICAL APPLICATIONS

Despite NMES often being commercially marketed as an effective modality for enhancing recovery from exercise, the overall findings of this review appear to provide insufficient evidence to support this. Whilst there appears to be good evidence to show that NMES can have a positive blood lactate lowering effect compared to passive recovery, as well as positive effects on subjective ratings of pain and overall well-being, there is no evidence to support its use for enhancing subsequent exercise performance compared to traditional recovery methods. Although the beneficial effects of NMES on subjective measures of pain and feelings of well-being should not be discounted and may provide some justification for

its use in some populations, the lack of evidence regarding its effects on actual athletic performance is likely the most important factor to consider for athletic populations.

For athletes who currently use, or are considering the use of NMES for the purpose of enhancing recovery from exercise, they are some important factors that need to be considered: 1) there is considerable heterogeneity of existing research protocols that have investigated NMES as an recovery modality, in terms of the NMES parameters used, mode of exercise, and duration of recovery periods; 2) when using NMES, considerable individual variability can exist in the stimulation intensity required. This can be due to factors such as adipose tissue variability, which can affect current to the stimulated region, as well as variability in an individual's perception of pain or discomfort when using NMES. This likely explains why there is no universal recommendation on the optimum NMES intensity that should be used during recovery from fatiguing exercise and why this needs to be selected subjectively on an individual basis. However, intensity likely needs to be high enough to induce sufficient muscle activation (for muscle pump effect) to promote metabolite clearance, without being too high, that will cause muscle fatigue.

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Figure 1: Article extraction selection process during Stages One and Two.

Table 1: Systematic Review Inclusion Criteria.

Table 2: Summaries of the selected studies from the data extraction process in Stages One and Two.

Table 3: Comparison of study variables for selected systematic review articles (Mean±SD).

Table 4: Extended Cochrane Collaboration's Tool for Assessing Risk of Bias Quality Assessment Tool (Extended portions are in italics) Taken from Higgins and Green (16).

819 **Table 5:** Risk of bias assessment of selected systematic review articles (modification of the
820 model used by vanTulder et al. (30).
821
822 **Table 6:** Meta-analysis of NMES vs. PAS recovery for blood lactate ($mmol.L^{-1}$) where fixed
823 or random effects models were used (10, 15, 20 min). Where there is little or no between
824 studies heterogeneity, results are reported as fixed effects, and where heterogeneity exists,
825 reported as random effects. Both 25 and 30 min show Forest Plots where a meta-analysis
826 was not applicable.
827
828 **Table 7:** Meta-analysis of NMES vs. ACT recovery for blood lactate ($mmol.L^{-1}$) where fixed
829 or random effects models were used (10, 15, 20 min). Where there is little or no between
830 studies heterogeneity, results are reported as fixed effects, and where heterogeneity exists,
831 reported as random effects. Both 25 and 30 min show Forest Plots where a meta-analysis
832 was not applicable.
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