Recent Advances in Health Sciences

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CONTENTS

Chapter 1 ........................................................................................................................ 1
Nursing Services in the Ottoman Empire
Behire SANÇAR

Chapter 2 ...................................................................................................................... 14
Posttraumatic Stress Disorder Among Veterans and Well-Being: What Can Nurses Do about It?
Derya ADIBELLI

Chapter 3 ...................................................................................................................... 26
What Is Nursing Informatics?
Hava GÖKDERE ÇINAR, Semra SÜRENLER, Nurcan ÖZYAZICIOĞLU

Chapter 4 ...................................................................................................................... 32
Transactional Analysis Approach in Patient-Nurse Communication
Zümrü ÜLKER DÖRTTEPE, İlkay KESER

Chapter 5 ...................................................................................................................... 43
The Pain Management in Intensive Care Units
Dilek YILMAZ, Yurdanur DİKMEN, Dilek KARAMAN

Chapter 6 ...................................................................................................................... 54
Responsibilities of Nurses in Use of Complementary and Alternative Medicine in Cancer Patients: Importance of Reflexology and Progressive Muscle Relaxation Exercises
Hacer ALAN DİKMEN, Füsun TERZIOĞLU

Chapter 7 ...................................................................................................................... 69
Patient Satisfaction and Quality of Care in Pediatric Settings
Bedriye AK

Chapter 8 ...................................................................................................................... 77
Preoperative Anxiety and Postoperative Pain for Tonsillectomy in Adult Patients: The Effect of Education and Follow-Up Telephone Calls
Rahşan ÇEVİK AKYIL, Nadiye ÖZER, Özgür YÖRÜK

Chapter 9 ...................................................................................................................... 87
The Disease of Our Time: Vitamin D Deficiency and Hypovitaminosis D
Elif ÜNSAL AVDAL, Yasemin TOKEM, Berna Nilgün ÖZGÜRSOY URAN

Chapter 10 ..................................................................................................................... 94
Abuse in Old Age and Nursery Approach
Çiğdem KAYA, Perihan SOLMAZ, Ebru KURDAL BAŞKAYA

Chapter 11 .................................................................................................................. 104
Strategies and Models for Evidence Based Nursing Practice
Yasemin YILDIRIM USTA, Songül ÇAĞLAR

Chapter 12 .................................................................................................................. 113
Use of Technology in Nursing Education
İlknur BEKTAŞ, Figen YARDIMCI
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>The Cost of Nursing Compassion Fatigue: <em>A Literature Review</em></td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>Yurdanur DİKMEN, Nasibe Yağmur FİLİZ, Handenur BAŞARAN</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Drug Errors and Nurses' Responsibilities for Their Prevention</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>Aylin PALLOŞ</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Physiology of Nervous System</td>
<td>148</td>
</tr>
<tr>
<td></td>
<td>Derya Deniz KANAN</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Pediatric Patient Safety</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>Figen YARDIMCI, İlknur BEKTAŞ</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Ergonomics in Delivery Rooms and its Importance</td>
<td>174</td>
</tr>
<tr>
<td></td>
<td>Nevin ÇITAK BİLGİN</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Pregnancy and Healthy Life Style Behaviours</td>
<td>183</td>
</tr>
<tr>
<td></td>
<td>Sezer ER GÜNERİ</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>The Use of Simulation in the Improvement of the Clinical Skill and Competency of the Nursing Students</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Yurdanur DİKMEN, Fatma TANRIKULU, Funda EROL</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>The Effects of Gestational Diabetes on Postpartum Period</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td>Gülşen IŞIK, Nuray EGELİOĞLU CETİŞLİ</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Results of Maternal Obesity</td>
<td>237</td>
</tr>
<tr>
<td></td>
<td>Nuray EGELİOĞLU CETİŞLİ</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Parents Attachment and Nursing Approach</td>
<td>243</td>
</tr>
<tr>
<td></td>
<td>Selma ŞEN</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Complementary and Alternative Medicine (CAM) in the Treatment of Infertility</td>
<td>249</td>
</tr>
<tr>
<td></td>
<td>Yasemin AYDIN, Merve KADIOĞLU</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Elderly Home Care Services</td>
<td>263</td>
</tr>
<tr>
<td></td>
<td>Nazife AKAN</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Non-pharmacological Methods Administered in Painful Interventional Procedures on Children</td>
<td>281</td>
</tr>
<tr>
<td></td>
<td>Fatma YILMAZ KURT, Aynur AYTEKİN, Sibel KÜÇÜKOĞLU</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 39 .................................................................................................................. 409
Supporting Memory Development in Early Childhood
Arzu ÖZYÜREK, Asya ÇETİN

Chapter 40 .................................................................................................................. 414
Role of Child Development Specialist in Early Intervention Process
Çiğdem AYTEKIN

Chapter 41 .................................................................................................................. 427
The Situation of the Children's Home in Turkey
Figen GÜRSOY, Fatih AYDOĞDU

Chapter 42 .................................................................................................................. 437
Normal Developing Siblings of Children Having Different Problems
Selvinaz SAÇAN

Chapter 43 .................................................................................................................. 452
Investigation of the Development of Premature and Non-Premature Children
Didem EMRE BOLATBAŞ, Müşriye YILDIZ BIÇAKÇI

Chapter 44 .................................................................................................................. 459
Epidemiology of Urinary Incontinence and Risk Factors
Ayten DİNÇ

Chapter 45 .................................................................................................................. 472
Approach to Inflammatory Bowel Diseases with Current Guidelines
Berna Nilgün ÖZGÜRSOY URAN, Elif ÜNSAL AVDAL, Yasemin TOKEM

Chapter 46 .................................................................................................................. 488
Balneotherapy and Health
Bülemt ÖZDEMİR, Levent ÖZDEMİR

Chapter 47 .................................................................................................................. 494
Color Stability of Provisional Materials Used in Dentistry
Ayşe Nurcan DUMAN

Chapter 48 .................................................................................................................. 508
Enteral Nutrition
Hülya KAMARLI, Aylin AÇIKGÖZ

Chapter 49 .................................................................................................................. 524
The New Favorite of Children and the Young: Energy Drinks
Selvinaz SAÇAN, Hakan Murat KORKMAZ

Chapter 50 .................................................................................................................. 532
Energy Drinks: Contents, Effects and Awareness of Consumption
Fatma ÇELİK KAYAPINAR, İlknr ÖZDEMİR

Chapter 51 .................................................................................................................. 547
Some Wild Plants Commonly Used in Folk Medicine in Turkey
Sefa AKBULUT, Mustafa KARAKÖSE
Chapter 52 .................................................................................................................. 560
Mobbing; Effects on the Mental Health and Protection
Nermin GÜR汉AN, Ebru KURDAL BAŞKAYA and Perihan SOLMAZ

Chapter 53 .................................................................................................................. 572
Smoking Behaviour Among High School Teachers in Turkey
Ayten DİNÇ

Chapter 54 .................................................................................................................. 580
The Effect of Developing Technology on the Family Structure and Family Relations
Derya ADIBELLI, Rüveyda YÜKSEL

Chapter 55 .................................................................................................................. 590
The Rules of Requirement in the Swimming Pools
Cemal GÜNDOĞDU, Evrim ÇELEBİ

Chapter 56 .................................................................................................................. 600
Gender Perspective on Leadership
Aslı ER KORUCU, Füsun TERZİOĞLU

Chapter 57 .................................................................................................................. 614
Legislation and Mobbing in Turkey
Nermin GÜRhan, Ebru KURDAL BAŞKAYA, Çiğdem KAYA

Chapter 58 .................................................................................................................. 623
Hospital Management and Organization in the Ottoman Empire
Bilal AK

Chapter 59 .................................................................................................................. 640
Network Analysis; Accessibility to Hospitals with Remote Sensing and Geographic Information Systems Techniques: A Case Study of KonyaAltı, Antalya-Turkey
Mesut ÇOŞLU, Serdar SELİM, Namık Kemal SÖNMEZ, Dilek KOÇ-SAN

Chapter 60 .................................................................................................................. 648
The Organization of the Health Care Services in Turkey
Sabahattin TEKİNGÜNDÜZ

Chapter 61 .................................................................................................................. 670
The Role of Teamwork in Patient Safety at Healthcare Institutions
Şerife Didem KAYA, Aydan YÜCELER

Chapter 62 .................................................................................................................. 690
Theories of Play in the Context of Leisure
Ali TEKİN, Gülcan TEKİN, Emrah AYKORA

Chapter 63 .................................................................................................................. 704
Determining Some Physical and Physiological Parameters of Undergraduate Students
Fatma ÇELİK KAYAPINAR, İlknur ÖZDEMİR
Chapter 64 .................................................................................................................. 711
Electrical Muscle Stimulation and Its Use for Sports Training Programs: A review
Fatih KAYA, Mustafa Said ERZEYBEK

Chapter 65 .................................................................................................................. 734
Prohibited Substance Use in Sports and Therapeutic Use Exemptions
Halil TANIR

Chapter 66 .................................................................................................................. 745
Exercise is Medicine
Gözde ERSÖZ

Chapter 67 .................................................................................................................. 759
Muscular Endurance Training with Electromyostimulation: Is It Possible Torque Production in Fatigue?
Fatih KAYA, Salih PINAR, Elif Sibel ATIŞ, Andrew P. LAVENDER, Mustafa Said ERZEYBEK
Chapter 67

Muscular Endurance Training with Electromyostimulation: Is It Possible Torque Production in Fatigue?1

Fatih KAYA*, Salih PINAR**, Elif Sibel ATIŞ***, Andrew P. LAVENDER****, Mustafa Said ERZEYBEK*****

1. INTRODUCTION

Electromyostimulation (EMS) has commonly been used to improve training outcomes for both muscle strength and fatigue resistance (Thériault et al., 1996; Brocherie, 2005). The effects of EMS have been observed in the recruitment pattern of motor units during voluntary contractions as it may reverse the order of motor unit recruitment known as Henneman’s size principle (Feiereisen et al., 1997; Porcari et al., 2002). According to the studies that support the size principle, when the muscle is stimulated using an external electrical stimulator large diameter motor units are preferentially recruited and conduct action potentials at higher speeds than axons of the smaller motor units. Electrical muscle stimulation may be an easy way to ‘train’ fast twitch motor units without great overall muscular effort (Gregory & Bickel 2005; Starkey, 2013). High frequency stimulation (>70 Hz) generates fatigue rapidly (Petrofsky, 2004). Therefore, artificial electrical stimulation of a muscle while it is conciously activated maximally, or near maximal contraction requires high frequency stimulation in order to cause fatigue (Hortobágyi, 1996).

Fatigue is accompanied by a reduction in maximal force generating ability of a muscle during voluntary actions. This is due partly to compromised of the central nervous system signal pathways (Boyas & Guével, 2011) and partly metabolic factors located within the muscle fibres lead to a decline in muscle force generated over sustained periods of activity (Komi, 2003; Gandevia, 2001; Kraemer et al., 2011). However, in order to develop muscular endurance the level of training is usually low or the load used for muscular workouts is set for a low to moderate intensity (Kraemer et al., 2002). Training at this intensity for long periods over many sessions is required in order to improve muscles ability to generate force for longer periods.

Nervous system adaptations to training can improve physical performance

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1 This study is derived from Kaya’s (2011) doctoral dissertation,
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Specialised, neural training sessions that improve the nervous system ability to produce sustained, high-frequency signals which allow a muscle to contract with its greatest force and physiological limit may be useful (Gandevia, 2001).

The size principle of motor unit recruitment states that slow twitch (ST) fibers are preferentially recruited and larger motor units are recruited as the smaller ones are lost to fatigue at low force output contractions. Electrical stimulation of fatigued muscles may activate more motor units. Exposing fast twitch (FT) muscle fibers to continuous high frequency stimulation might decrease the stimulation threshold of the fibers causing them to be recruited earlier. Therefore, it was suggested that facilitating FT fibers recruitment with electromyostimulation would develop an ability to recruit these fibers more efficiently during a fatigue inducing contraction resulting in an improvement in the capability to maintain force output during the state of fatigue.

Although electrical stimulation training of muscles with high frequency have beneficial effects on muscle strength and performance parameters little is known regarding the neuromuscular adaptations during fatigue.

The aim of the present study is to investigate whether high frequency electrical stimulation incorporated into an eighth week endurance training programme could affect the capability of torque production of the fatigued quadriceps muscle.

2. MATERIALS AND METHODS

2.1 Subjects

Twenty healthy male university students from the Department of Physical Education and Sports, who do not participate in any regular exercise training (age range 20-25 years) volunteered for this study.

Subjects were matched according to their initial maximum voluntary torque values of quadriceps muscle and divided into electromyostimulation (EG, n=9, age 21.89±2.67 yrs, height 176.78±8.80 cm, body weight 71.00±9.10 kg) and control groups (CG, n=11, age 21.45±2.07 yrs, height 180.18±8.54 cm, body weight 79.82±10.91 kg) and assigned to one of the groups.

Approval for the study was obtained from the University’s Faculty of Medicine Ethics Committee and all volunteers gave written informed consent to participate in accordance with The Declaration of Helsinki.

2.2. Experimental design and testing

Training Program

Before the training program, EG participated in a familiarisation session with electrical stimulation and the test protocol. During this session, each subject’s maximum exercise intensity of (load level-weight) for training sessions was defined by their 1RM, defined as the maximum weight that a full repetition can be completed but two repetitions could not. Each participant in both groups was asked to continue their regular diet and exercise routines throughout the duration of the experiment.

Both groups participated in a muscular endurance training program for a period of eight weeks. EG participated in electrical stimulation sessions along with this program (Table 1). In accordance with muscular endurance training recommendations of the American College of Sports Medicine, training sessions were performed on three non-consecutive days each week across the eight weeks (Hoeger Werner & Moore, 2002).

Each training session consisted of three stages: 1) Ten minutes warm-up period
(cycling / treadmill / stretching exercises), 2) Three sets of muscular endurance exercise on a knee extension machine for knee extensor muscles of both legs until exhaustion at a resistance of 40% of each individual’s 1RM (10-20 min) and 3) Ten minutes cool-down period (stretching).

Table 1: Training program

| Mode: Muscular endurance training + Electrical stimulation (only for EG) |
| Training session: knee extension on knee extension machine |
| Target muscle group: Quadriceps |
| Sets: 3 sets a day |
| The number of repetitions: until voluntary fatigue |
| Resting: 30 sec (EG received electrical stimulation during rest) |
| Intensity/load: % 40 1 RM-fixed |
| Determination of voluntary fatigue: |
| (1) subjective with feedback method (Borg scale) |
| (2) not being able to move against resistance with appropriate range of motion. |
| Frequency: 3 sessions per week (nonconsecutive days) |
| Duration: 30 min- 40 min (10 min warm-up, 10-20 min training, 10 min cool-down). |
| EMS parameters: tolerable stimulation intensity, high frequency (50 Hz) for 30 sec (knee joint angle 60°). |

Table 2: Parameters of Electrical Stimulation

| 1. Waveform: biphasic, rectangular, symmetrical |
| 2. Intensity (amplitude): 10 mA-90 mA (subject tolerance) |
| 3. Pulse width (pulse duration / impulse width): ≥ 200μs |
| 4. Frequency (number of impulse every second): 50 Hz (fixed frequency). |
| 5. Ramp up time: 0 s. |
| 6. Ramp down time: 0 s |
| 7. Stimulation time: 30 s. (contraction time is 1 s, relaxation time 1 s.) |

When voluntary fatigue was reached, the CG were instructed to rest while the EG received electrical muscle stimulation for 30 s (Table 2). To achieve a strong muscle contraction the intensity of electrical stimulations were delivered at an intensity which was at the tolerance threshold for each individual (mean: 26.48±2.66 mA). Three sets of fifteen contractions were performed.

The mean value of electrical stimulation intensity, the loads used in training (weight) and training session duration of each subject were strictly controlled and were recorded by the researchers at the end of each session. In addition, all subjects were asked to specify their subjective evaluations during stimulation (pain, muscle cramps or any other discomfort) and these comments were noted. The weights that the subjects lifted were increased according to 1RM in 2-week intervals (muscular adaptation).

Application of Electrical Stimulation

During the stimulation, subjects were seated on a knee extension machine with the knee joint fixed at an angle of 60°. Electrical stimulation was applied simultaneously to quadriceps muscles of both lower extremities via self-adhesive surface electrodes.

Positive electrodes (5 cm×5 cm) were placed onto the motor points of the vastus medialis and vastus lateralis muscles, the negative electrodes (5 cm×10 cm) were placed on the quadriceps femoris ~ 5 cm below the inguinal ligament as described by Delitto.
and Robinson (1989). A motor-point pen of a Compex-MI Sport electrical stimulation device (Medicomplex SA, Ecublens, Switzerland) was used to determine the motor point. A four-channel EMP4 Expert device (Schwa-Medico, Ref 1040042, Germany) was used for the electrical stimulation. Electrical stimulation parameters are shown in Table 2.

**Test Procedure**

All groups were tested at the pretraining session and at the end of 4 and 8 weeks of training. The test battery included measurements of: a) rested maximum voluntary torque b) maximum voluntary torque at fatigue, c) muscular endurance (fatigue index-FI).

Height and weight of subjects’ were measured with a standard laboratory stadiometer and a scale at baseline and weight measurements were repeated at the end of weeks 4 and 8. 1RM measurements were taken at baseline and repeated at intervals of two-weeks.

**1RM Procedure**

The maximum amount of weight lifted for one repetition, or 1RM, for each subject was determined by using both lower extremities with knee extension machine. Subjects initially performed 1-2 set of warm-up executing 5-10 repetitions at 40-50% of their own estimated 1RM, they were then asked to lift progressively heavier weights to the maximum achievable level. Subjects were then asked to perform one set of knee extension at their maximum level and perform as many repetitions as possible. The following formula was used to determine a subject’s 1RM (Spanos et al., 2007):

\[
1\text{RM} = \left[ \frac{\text{number of repetitions}}{30} + 1 \right] \times \text{weight in kg.}
\]

**Isokinetic test protocol**

The capability of force production during the fatigue was tested using an isokinetic dynamometer, Cybex NORM dynamometer (Cybex, division of LUMEX, Inc., Ronkonkoma, New York, USA) on the dominant leg with a three-step protocol as described in Figure 1.

Each test was performed at the same time of the day with a warm up period of 10 min (bicycle ergometer, ~40W, 5-7 min + stretching) and lasted 30 min. Subjects were asked to avoid caffeine drinks within one hour, large meals within two hours and excess alcohol the night before the tests.

Each subject was seated with their hip angle between 75 and 90 degrees of flexion on the isokinetic dynamometer. The rotation axis of the isokinetic dynamometer was aligned with the anatomical axis of the subject's knee, and the lever arm was attached to the subject's leg at a distance of approximately 70% of the length from the medial knee joint line to the medial malleolus to allow for a standardized and comfortable position. The subject's thigh was stabilized with a canvas strap fixed to the dynamometer.

While subjects were seated on the dynamometer, they performed five sub-maximal extensions and flexions for familiarization purposes (Kannus, 1994).

Each participant performed the required maximal concentric knee extension repetitions through the range of motion from 90° to 0° of knee flexion at 60°/s -100°/s angular velocity, with a passive return to 90° (no quadriceps eccentric or concentric hamstring activity).

During the tests, participants were continuously encouraged verbally to perform
with maximal effort. Each subject’s Maximum voluntary torque was measured while performing four maximal isokinetic-concentric quadriceps contractions at 60°/sec angular velocity. This test was repeated after the muscular endurance test.

Muscular endurance was measured using the fatigue protocol developed by Thorstensson and Karlsson (Brown & Weir, 2001). Each subject performed a fatigue test consisting of 50 maximal knee extensions at 180°/s angular velocity using the Cybex isokinetic dynomometer. They were paced at a rate of 50 extensions per minute by use of a metronome, the subjects were instructed to maximally extend their legs with every repetition.

![Isokinetic test protocol](Image)

**Figure 1: Isokinetic test protocol**

### 2.3 Statistical Analysis

Force output data were statistically evaluated using between and within subjects comparisons with repeated measures design (Mixed-model Ax(BxS) and Ax(BxCxS) Design).

Independent samples t tests were used to compare baseline data between groups. At each re-test, to assess the effects of the training on 1RM and fatigue index, values were analyzed using a two-way (training / time) mixed analysis of variances (two-way (2x3) Mixed ANOVA). A three-way (group / time / test) mixed analysis of variance was used to evaluate peak torque scores before and after fatigue at baseline, week 4 and week 8 of training. Multiple comparisons using Bonferroni verification with checks for sphericity were carried out.

The level of significance was set at p ≤ 0.05 for all procedures and statistical analyses were undertaken using the SPSS 17.0 software.

### 3. RESULTS

There were no significant differences among baseline values of body weight (t(18)=-1.93, p>0.05; 1RM t(18)=-0.55, p>0.05; and peak torque t(18)=-0.73, p>0.05 between groups.

Mean increase in duration of the training session for EG was 149.50 % (from 3.98±0.80 to 9.93±5.05) while it was 65.22% for CG (from 3.45±0.63 to 5.70±2.29) at the end of 8th week compared with the first week. Training loads of the EG increased by 32.72 % (from 36.67±6.26 to 48.67±6.12) while the increment was 19.92% (from 38.36±6.91 to 46.00±5.77) for the CG at the end of the 8th week (Table 3).

1RM scores increased for both groups at the end of the 2nd week and increased further by the end of week 8 linearly. The average change between initial and final test scores for the EG was 39.85% for 1RM (from 91.99±16.06 to 128.65±15.82), the average change for the CG was 24.50% (from 96.14±17.54 to 119.69±16.65). There were no significant differences in the average 1RM scores between EG (\(\bar{X} = 112.32\)) and CG (\(\bar{X} = 108.32\)), F (1, 18) = .368, p = .552, \(\eta^2 = .020\) across the eight weeks (Figure 2).
Table 3: Training duration and training loads mean values of EG and CG. EG's values higher than CG's throughout the process. Mean (SD)

<table>
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<tr>
<th>Training duration (sec)</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline Wk4 Wk8</td>
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<td>Baseline</td>
<td>3.98(0.80) 7.64(3.99) 9.93(5.05)</td>
</tr>
<tr>
<td>Wk4</td>
<td>36.67(6.26) 42.33(7.27) 48.67(6.12)</td>
</tr>
<tr>
<td>Wk8</td>
<td>3.45(0.63) 3.61(0.38) 5.70(2.29)</td>
</tr>
<tr>
<td></td>
<td>38.36(6.91) 41.50(6.63) 46.00(5.77)</td>
</tr>
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Figure 2: 1RM changes were similar for both groups throughout the study, p>.05. (+/-1 SE).

Mean peak torque scores and the percentage changes for before and after fatigue at each test point are shown in Figure 3.

Mean peak torque scores (60°/s) of both groups increased linearly from baseline throughout the final testing. The mean peak torque score changes of both groups were similar at each test point before and after fatigue, F (2.36) = .352, p = .706, $\eta^2 = .019$ (Figure 4) (group x time x test interaction effect).

When group and test factors were ignored (time main effect) there was an increase in the mean peak torque scores of time period (F (2.36) = 22.289, p = .000, $\eta^2 = .553$), and these increases were similar between the groups (F (2.36) = .032, p = .969, $\eta^2 = .002$), (group x time interaction effect). At the end of 4th and 8th week the average peak torque scores were higher comparing to baseline scores (p<.01). Maximum voluntary torque increase in EG was 11.17%, while it was 10.61% in CG.

Fatigue index scores in both groups decreased at the end of the 4th week and this decrease continued linearly for the CG until the end of the 8th week. The average decrements in the fatigue index between baseline and the final test was 18.53% for EG (from 61.78±7 to 50.33±8.32) while it was 8.53% for CG (56.36±10.23 to 51.55±7.81) (Figure 5).
For both groups, the mean fatigue index score changes differed across the three time points, $F(2, 36) = 3.339, p = .047, \eta^2 = .156$. Multiple comparison test results
showed that this difference is significant in EG, between baseline and the 4th week (p<.05) and between baseline and the 8th week (p<.01), and there was no significant difference in CG (p>.05) (Figure 5).

Figure 5: Changes in the fatigue index throughout the process in EG and CG, *p <.05 compared with baseline values. (+/-1 SE).

4. DISCUSSION

EMS has been employed for strength training in many studies but the capability of torque production of fatigue induced muscles has been poorly investigated. The present study hypothesised that electrical stimulation with 50 Hz of fatigued muscle during 8 week endurance training would enhance the torque production capability. The authors of this study were careful to ensure that stimulation parameters used in the protocol were at a level to prevent muscular fatigue since high-frequency stimulation is known to produce excessively strong contractions that induce fatigue (Binder-Macleod & Snyder-Mackler, 1993). A stimulation cycle with a short ‘on’ time and a long ‘off’ time is more effective for preventing muscle fatigue and enhancing muscle strength gains (Packman-Braun, 1988; Matsunaga et al., 1999).

50 Hz frequency stimulation was applied between sets in this study. Frequencies of 30–50 Hz are far above the natural firing frequencies of quadriceps muscles motor units which usually function between 15Hz - 25Hz in normal voluntary contractions (De Luca, 1997). However, a previous study suggests that higher frequencies of 30 to 50 Hz are more effective than lower ones for improving endurance with exercise (Glaviano & Saliba, 2016). To our knowledge a muscle can almost reach maximum contraction with electrical stimulation at 50 Hz (Hultman, 1995). It’s been shown that to produce repetitive knee movements, higher frequency trains were better than lower frequency...
trains (Kebaetse et al., 2002).

Following 8 weeks of training the duration of training sessions for both groups were longer compared with baseline, 149.50% for EG and 65.22% for CG. The greater improvement in the EG may be due to the effect of electrical stimulation on intramuscular enzyme activity although the authors can only speculate regarding this as no enzyme activity measures were made for this study. This finding is important for interpreting the results of the isokinetic tests, as the overall training volume was greater for the EG compared with the CG which suggests a faster adaptation to training.

Similar to the duration of training sessions, 1RM scores in both groups showed a linear increase during the training period. The average increase in 1RM score was slightly greater for EG although there was no significant difference compared with CG. The training loads for EG (mean change from baseline 32.72%, from 36.37±5.92 to 48.26±6.31) increased more rapidly than for CG (mean change from baseline 19.92%, from 38.51±7.10 to 45.95±5.78) at the end of the training period.

Results of training duration and load showed that EG could exercise with more heavy weights and longer duration than CG. Robinson and Snyder-Mack (2007) reported that the contractile model during high frequency electrical stimulation with heavy load leads to increase in muscle strength related to intramuscular changes even though there was a rapid onset of fatigue (Robinson & Snyder-Mackler, 2007). Duration of the training sessions, training loads, 1RM scores and subjective feedback obtained from participants together explain the development of muscular endurance. Regarding subjective feedback from EG, an example of a typical comment was “not very tired, this was not so hard" supports the improvement of muscular endurance in isokinetic tests.

Maximum voluntary torque increased linearly during the eight weeks of training for both groups. This finding shows that training with or without electrical stimulation is effective for improving the ability to produce torque. The changes in mean peak torque score were similar in both groups for all measurement points. Therefore the hypothesis in the present study, that the capability of producing torque while in a state of fatigue would be greater in EG whom received electrical stimulation compared with CG was not supported. When the mean changes were evaluated for all tests EG achieved better results from the training program than CG. The peak torque increments were greater for EG than CG after fatigue while scores were higher for CG compared with EG before fatigue. Although there was no significant difference between groups for the mean peak torque, EG had better scores after fatigue at the end of the 4th week than CG. The lack of torque production of fatigued induced muscles for EG might be due to the frequency (50 Hz) applied in this study was not high enough. Such an interpretation like increasing the frequency periodically during the training program or applying various frequency components of electromyostimulations might obtain more effective outputs.

The mean change in the fatigue index for EG was 18.53% while it was 8.53% in CG. Interestingly, EG had a significant increase in muscular endurance across the training period while CG had no significant increase. It is possible to explain the significant improvement of muscular endurance with the effects of electrical stimulation in EG. The effect of electrical stimulation at the end of 4th week was important in particular, while it’s considered that a significant improvement observed at the 4th week and the improvement was slower after 4 week to the end of 8th week. Possible
explanations to that might be the subjects adapted to this frequency physiologically after four weeks. Electrical excitation may have resulted in an adaptation response causing some FT fibers (type IIA) to express ST characteristics (Brown et al., 1989) such that high frequency stimulation combined with long term muscle strengthening exercise demonstrated an increased fatigue resistance (Marqueste et al., 2003; Selkowitz, 1985). One reason for this fatigue resistance may be that a contraction with EMS is different from a voluntary contraction in terms of motor unit firing frequency, recruitment order and synchronicity. Previous research showed that, it is possible to obtain significant effects by electromyostimulation when applied for 3 training sessions per week for 4 weeks (Parker et al., 2003). Training with electrical stimulation decreases muscular endurance rate rapidly at first. This may be due to neural adaptive mechanisms. Spinal Motoneuron pool’s increased activation could be one potential reason of this adaptation (Hortobágyi, 1996).

In the present study training at a moderate intensity accompanied by application of high-frequency electrical stimulation might lead to an accumulation of lactate in the quadriceps muscles of the EG that would be expected during high intensity exercise. Increasing the intensity of exercise leads to an increase in accumulation of lactate in the muscles (Sovndal & Murphy, 2005). Anecdoal feedback from the EG participants suggests that their perception of fatigue was greater than CG. However the comments about fatigue decreased at the end of 4th and 8th week compared with baseline. This may be due to positive changes of intramuscular enzyme activities with training and electrical stimulation. It may be suggested that the adaptations of an increase in mitochondrial density, oxidative capacity and capillary density result in this change in perception. Finally, the results of the study do not support our hypothesis that the fatigued muscles which received electrical stimulation (50 Hz) with training would produce more torque than muscles that were trained without electrical stimulation. However, electrical stimulation is an effective method for inducing intramuscular changes in peak torque and muscular endurance. It may be possible to get different results by investigating stimulation at other frequencies and different training methods.

5. CONCLUSION

The results of the present study demonstrate that, the addition of the electromyostimulation (50 Hz) to training had no extra benefit to enhance torque production of fatigued quadriceps. However, it can be suggested to add EMS to the training programme for the short training periods for muscular endurance. Further investigation is required in order to establish whether training increased in the ability to produce force can be enhanced with electrical stimulation focusing on various stimulation frequencies.

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