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Training-induced changes in muscle contraction patterns enhance exercise performance after short-term neuromuscular electrical stimulation

Gökhan Umutlu[a,*], Nevzat Demirci[b] and Nasuh Evrim Acar[b]
[a] *School of Physical Education and Sports, Final International University, Kyrenia, Northern Cyprus*
[b] *Faculty of Sports Sciences, Mersin University, Mersin, Turkey*

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Abstract.
BACKGROUND: Neuromuscular electrical stimulation (NMES) is a complementary tool for therapeutic exercise for muscle strengthening and may potentially enhance exercise performance.
OBJECTIVE: To determine whether high-intensity interval training (HIIT) and continuous aerobic training (CA) coupled with NMES enhance the changes in the eccentric/concentric muscle contraction patterns of hamstring and quadriceps.
METHODS: Forty-five healthy sedentary male participants performed cycling training 3 times per week for 8 weeks combined with/without NMES performed at a load equivalent to 65% and 120% of $_{I}\mathrm{VO}_{2\mathrm{max}}$ (intensity associated with the achievement of maximal oxygen uptake). Anthropometrics, blood lactate measurements, $_{I}\mathrm{VO}_{2\mathrm{max}}$, $\mathrm{T_{Lim}VO_{2max}}$ (time-to-exhaustion) and isokinetic strength parameters were measured at baseline and post-training using a randomized controlled trial.
RESULTS: The conventional hamstring-to-quadriceps-ratio (HQR: Hcon/Qcon) at 60°/s and the Dynamic Control Ratio (DCR: Hecc/Qcon) at 180°/s significantly increased both in the dominant (D) and non-dominant (ND) limb in the HIIT + NMES group ($p < 0.05$). There was a positive significant correlation between the individual changes in D HQR at 60°/s and $_{I}\mathrm{VO}_{2\mathrm{max}}$ ($r = 0.94$, $p = 0.005$) and the DCR at 180°/s and $\mathrm{T_{Lim}VO_{2max}}$ ($r = 0.90$, $p = 0.015$), respectively.
CONCLUSIONS: The increases in the eccentric muscle contraction and DCR following HIIT + NMES seem to improve fatigue tolerance, cause less fatigue and oxidative stress on the lower limb during pedaling at high intensities.

Keywords: Blood lactate concentration, conventional and functional H:Q ratio, isokinetic strength, time to exhaustion, maximum oxygen consumption

1. Introduction

Muscle injuries are the most common sports-related injuries and the rate of in-season injury incidence was reported 4 times greater (16.5% vs. 4.1%) in athletes with HQR (cut-off point 0.60 and lower) and DCR (cut-off point 1.40 and lower) asymmetries resulted from an antagonist-agonist strength discrepancy compared to those have symmetrical muscle strength [1]. As a relevant data point, it can be observed that when using the HQR (Hcon:Qcon at 60 and 240°/s), more than 30% (55% and 38%) of the imbalances that were manifested while using the DCR went undetected [2]. To date, the effect of the peak moment ratio of knee

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[*] Corresponding author: Gökhan Umutlu, Final International University, School of Physical Education and Sports Department, Toroslar Avenue, No:6, 99370, Catalkoy, Kyrenia, Northern Cyprus. E-mail: gokhan.umutlu@final.edu.tr.

flexors and extensors on the risk of injury in the lower limbs has been extensively discussed in the literature [3–7]. Nevertheless, no reports to date have investigated whether the changes in eccentric and concentric muscle contraction patterns of hamstring and quadriceps muscle groups following HIIT and CA coupled with high-and-low-frequency NMES affect $_{I}\mathrm{VO}_{2\mathrm{max}}$ and time to exhaustion tolerance during this intense exercise.

Muscle recruitment patterns and the modulation of musculotendinous architecture in the lower extremity have an essential role to enhance movement coordination in cycling [8]. In terms of delayed onset of increased local muscular fatigue during cycling, an improved bioenergetics capacity and optimization of quadriceps and hamstring muscle recruitment are desirable for producing power at the pedal to maintain high mechanical propulsive efficiency [9,10]. Understanding the relationship between the distribution of muscular strength and aerobic capacity is important, as such information can advance training methods and thus improve endurance cycling efficiency. However, the effectiveness and necessity of strength training for endurance athletes specifically in cycling has been an ongoing debate for many years among athletes, coaches, and sports scientists [11]. Whereas, strength discrepancies in the lower extremity may be transferable to the mechanics of endurance cycling. Therefore, the increase in exercise load that accompanies endurance cycling causes muscle damage, fatigue and muscle pain and increased local muscular fatigue may also lead to a decreased mechanical efficiency, poor technique and/or imbalance of force generation [12]. Moreover, it was reported that a 12% reduction in maximal voluntary contraction moment of the knee extensors was accompanied by a reduction in voluntary activation of 13–16% following 30 min cycling exercise performed at an intensity corresponding to 80% of the maximal aerobic power although this depended on the rate of pedaling [13–15].

NMES, a complementary tool in sports medicine, has been utilized for the maintenance of muscle mass and strength [16]. It has been shown to improve lower limb muscle strength and cardiorespiratory exercise capacity simultaneously in sedentary healthy individuals [17]. It was also reported that NMES simultaneously improve the indices of cardiovascular exercise capacity with an increase of 10% in maximum aerobic capacity ($\mathrm{VO}_{2\mathrm{max}}$) following daily stimulation (rhythmical continuous contraction at a frequency of 4 Hz for 1-hr) over a 6 to 8 week period seen in sedentary populations [18]. However, the combined application of NMES and volitional contractions suggested being more effective for muscle strengthening than NMES or volitional contractions alone [19].

Cycling exercise is one of the most common aerobic exercise intervention to improve exercise capacity or physical fitness [21–24]. However, the effects of cycling exercise on muscle strengthening has not been demonstrated [25] while cycling exercise has also been reported to improve muscle strength of the lower extremity [26]. In our study, cycling exercise performed at an intensity corresponding to 65% and 120% of the maximal aerobic power involves interactions of neuromuscular, aerobic and anaerobic components. However, whether cycling exercise combined with high-and-low-frequency NMES improve neuromuscular performance or the acute changes in HQR and DCR resulted from these adaptations improve $\mathrm{VO}_{2\mathrm{max}}$ and time to exhaustion performance is unknown. To the best of our knowledge, this is the first report of HQR and DCR applied to functional tasks using an additional high-and-low-frequency NMES intervention ($_{I}\mathrm{VO}_{2\mathrm{max}}$ and $\mathrm{T}_{\mathrm{Lim}}\mathrm{VO}_{2\mathrm{max}}$) that are specific to sport (cycling). Therefore, the purpose of this study was two-fold. (a) First, to determine whether 8-weeks of HIIT and CA performed at 120% and 65% of $_{I}\mathrm{VO}_{2\mathrm{max}}$ coupled with NMES on a cycle ergometer induce different adaptations on neuromuscular performance, $_{I}\mathrm{VO}_{2\mathrm{max}}$ and $\mathrm{T}_{\mathrm{Lim}}\mathrm{VO}_{2\mathrm{max}}$ compared to HIIT and CA training alone (b) Second, to examine time to exhaustion tolerance at which $_{I}\mathrm{VO}_{2\mathrm{max}}$ and its relationship to differences in the eccentric/concentric muscle contraction patterns of hamstring and quadriceps muscle groups among the 4 trained states.

2. Methods

2.1. Participants

A total of 45 healthy male individuals with no history of physical disorders and physiological disease that developed in the last 2 years or any discomfort associated with the circulatory system, with at least 3 years of sports history, voluntarily participated in this study (age: 22.34 ± 1.27 years, height: 178.91 ± 5.67 cm, weight: 73.79 ± 7.61 kg, lean mass: 65.62 ± 7.34 kg, percent body fat: 14.15 ± 4.77%), respectively.

The participants were recruited based on the following inclusion criteria: having run (a) must be a student in physical education and sports department at the time of the study, and (b) who had participated in physical activities at least 2 times per week over the last 3 years. Students who have any musculoskeletal injury or hamstring and/or quadriceps injury in the past 6 months; overt metabolic, endocrine, cardiovascular, neurological, or metabolic diseases; consumption of medications or using any drugs that may influence the energy metabolism system were excluded from the study. Before participation, all the participants were informed about the experimental procedures, and the possible risks and discomforts associated with the study. All participants gave written informed consent before participating in the study approved by the Mersin University Institutional Review Board (Protocol number: 2018/22; Date of approval: 11/01/2018) in compliance with the ethical standards of the Helsinki Declaration.

2.2. *Study design*

A randomized controlled trial with a parallel-group study design was used. Participants were randomly assigned to either the experimental group or the control group. The Control group did not receive the treatment. The experimental group underwent one of HIIT and CA training groups without NMES or HIIT + NMES and CA + NMES with simultaneous NMES to investigate the effects of the NMES stimulus combined with HIIT and CA training on oxygen kinetics, time to exhaustion, isokinetic peak moment parameters.

2.3. *Procedures*

The training sessions were conducted three times per week throughout 8 weeks with a one-day interval. All trainings started 1–2 days after the pre-test session. For each participant the training intensity was set individually and all were instructed to maintain their usual food intake, hydration, and physical activity. No additional strength training was allowed during the study period.

2.4. *Anthropometric measures*

The anthropometric parameters were assessed using bioelectrical impedance analysis (Tanita 418-MA Japan) before Cybex isokinetic sessions. Height was measured through a stadiometer in the standing position (Holtain Ltd. U.K.).

2.5. *Isokinetic strength measurements*

Participants were tested on Humac Norm CSMI Cybex isokinetic dynamometer in the supine position and were encouraged throughout the test. Gravity correction was performed before the test. Before the assessment of isokinetic strength parameters of D and ND legs, the participants were seated in the upright position with the hips flexed at an angle of 90° and a series of 10 sub-maximal repetitions both during knee flexion and extension at 180°/s followed by 5 maximal bilateral knee extension repetitions, from 90° of flexion to full extension (0°), at both 60°/s and 180°/s. The D leg was chosen as the leg used to kick a ball. Gravity correction was made before all test sessions. The measurements of eccentric and concentric muscle performance under isokinetic conditions were performed with a range of motion in the knee joint of 90° (from 90° to 0°).

Conventional and dynamic control ratios were calculated for all training modalities. We used 60°/s angular velocity to assess HQR, i.e. $\mathrm{H}_{\mathrm{con}60}/\mathrm{Q}_{\mathrm{con}60}$, since this speed best illustrates the failure of power production in the muscle and possible power deficits are best noticed at low concentric mode speed. On the other hand, no D side effects were reported when the power of the Q and H were measured concentrically at the same speed (60°/s and 180°/s) [27]. However, it was suggested that the reliability of concentric and eccentric results at 60°/s may not be valid due to the coefficients of variation (8.1 vs 17.4%) between these muscle contractions [28]. On the other hand, we the DCR was derived from the higher speed i.e. $\mathrm{H}_{\mathrm{ecc}180}/\mathrm{Q}_{\mathrm{con}180}$ as this speed better reflects the actual agonist-antagonist muscle interaction specifically at high angular velocities. Aagaard et al. have observed that the higher the angular speed of the knee extension, the closer the DCR approximates unity [29]. Similarly, in another study, DCR was found to have a higher value at 120°/s (0.87) compared to at 60°/s (0.81) [30]. To screen the differences from baseline to follow-up measurements among all groups mean and standard deviation of the HQR and DCR were expressed in percentage (%) for both D and ND limb.

2.6. *Assessment of VO_{2max}, $_{I}VO_{2max}$, and time to exhaustion*

$\mathrm{VO}_{2\max}$, $_{I}\mathrm{VO}_{2\max}$, and T_{Lim} were measured in a preliminary test session using Ergoline Ergoselect 100/200 cycle ergometer over a one-week interval. In the first visit, a progressive cycle ergometer test was used to determine $\mathrm{VO}_{2\max}$ and $_{I}\mathrm{VO}_{2\max}$. Participants started to pedal at 50 Watt and were asked to pedal between 95–100 rpm. Each stage consisted of 2 min and load was increased 50 Watt with the completion of every stage until a plateau in VO_2 despite an increase in cycling intensity, a respiratory exchange ratio (RER) above 1.1, and 90% of the predicted maximal HR. If the stage of 2 min could not be completed, the load of the previous stage was recorded as $_I\text{VO}_{2\text{max}}$. The load that $\text{VO}_{2\text{max}}$ elicit was recorded as $_I\text{VO}_{2\text{max}}$ and was used to determine T_{Lim} and individual training intensity used during HIIT and CA training. Throughout the test, the Borg scale was used in the assessment of perceived exertion during exercise.

In the following session, T_{Lim} at $_I\text{VO}_{2\text{max}}$ test was carried out at a constant load until volitional exhaustion. Following a 10-min warm-up period at 60% of $_I\text{VO}_{2\text{max}}$, the load was immediately increased (in less than 20 s) up to $_I\text{VO}_{2\text{max}}$ and the participants were encouraged to pedal at a constant speed of 100 rpm to their volitional exhaustion. O_2 was measured breath by breath (CareFusion MasterScreen CPX, Germany) and subsequently averaged over 15-second intervals. Before each test, the automated gas analyzer was calibrated according to the manufacturer's recommendations. Heart rate was also monitored and recorded throughout $\text{VO}_{2\text{max}}$ and T_{Lim} test sessions using 12-lead ECG. Individual training intensity was determined using baseline $_I\text{VO}_{2\text{max}}$ parameters. VO_2 parameters of each participant were measured during each session throughout 8 weeks of training.

2.7. Collection of blood samples

In each $_I\text{VO}_{2\text{max}}$ testing session (pre-post) and at the end of every 2min interval during $_I\text{VO}_{2\text{max}}$ test blood samples were collected from earlobe using Lactate Pro 2 handheld analyzer (LT-1730, Arkray Inc, Kyoto, Japan). Blood samples were also taken before T_{Lim} and 2 min after the intervention to determine blood lactate concentrations. All participants were also instructed to maintain their usual nutrition throughout the study period. No nutrition supplements were allowed during the study period and all participants' nutrition on the test days was recorded.

2.8. Neuromuscular electrical stimulation protocol

NMES protocol was conducted using a 'COMPEX SP4.0 (Medicompex SA, Ecublens, Switzerland) 4 channel electric muscle stimulator. Biphasic symmetric rectangular pulsed currents (150 Hz) lasting 400 μs were used. COMPEX self-adhesive electrodes were used during muscle stimulation with COMPEX device. Positive snap electrodes (5 cm × 5 cm) that stimulate a 25 cm^2 area of the muscle surface which also has a membrane depolarization feature were placed on the proximal insertion of vastus medialis and vastus lateralis. The other negative electrode (10 cm × 5 cm), measuring 50 cm^2 was placed over the femoral triangle, 1–3 cm below the inguinal ligament.

2.9. Training regimen

Each HIIT session consisted of a 5-min warm-up (65% $_I\text{VO}_{2\text{max}}$) followed by 1-min exercise at 120% of the $_I\text{VO}_{2\text{max}}$ followed by 1-min "loadless" cycling. This interval was repeated 8 times on training days 1 and 2 and progressed to 14 repeated intervals by the eighth session. Participants were given strong verbal encouragement and asked to maintain pedal cadence at 100 rpm throughout the test session. Participants assigned to HIIT + NMES training group continued the same training protocol using an additional NMES protocol (Duration: 12 seconds "On" 8 seconds "Off", Intensity: 45–60 Hz, Current: 300 μs, Wave: Square waveform) throughout the 8 weeks. CA training was performed with the work rate set individually based on the participant's pre-training $_I\text{VO}_{2\text{max}}$ for 30–48 min. The duration of training was determined at 30 min for the first 2 weeks of training, 36 min for weeks 3–4, 42 min for weeks 5–6, and 48 min for weeks 7–8. Participants were asked to maintain the cadence rate at 80 rpm throughout the test. Participants assigned to CA + NMES training group continued the same training protocol using an additional NMES protocol (Duration: 20 seconds "On" 20 seconds "Off", Warm-up frequency: 3 Hz, Training Intensity: 20 Hz, Current: 300 μs, Wave: Square waveform) throughout 8 weeks.

2.10. Statistical analyses

The Shapiro Wilk-W test analysis of normality of distribution was followed by a two-way mixed ANOVA with repeated measures to analyze the results obtained for the subgroups before and after treatment (groups vs. pre/post-treatment). To analyze the results obtained for all groups before and after treatment; the Wilcoxon test for paired, Mann-Whitney U test for non-paired and, to compare the results overtime a Kruskal-Wallis test with Bonferroni correction were performed for non-paired data. Correlations were assessed using the Pearson product-moment correlation coefficient. Intraclass Coefficient (ICC) and Intraclass

Table 1
Comparison of pre-to-post-test anthropometric and physiological parameters among groups

Variable	Control ($n = 9$)	HIIT ($n = 9$)	HIIT + NMES ($n = 9$)	CA ($n = 9$)	CA + NMES ($n = 9$)
Body mass (kg)					
Before	76.21 ± 7.35	78.31 ± 7.12	75.20 ± 3.75	69.11 ± 9.24	74.31 ± 7.85
After	77.12 ± 7.19	77.20 ± 8.42	73.32 ± 3.41	68.42 ± 11.27	73.45 ± 6.65
Lean weight (kg)					
Before	62.20 ± 3.57	65.21 ± 3.60	64.67 ± 3.77	61.87 ± 8.18	67.40 ± 4.57
After	63.91 ± 4.59	65.45 ± 3.36	65.73 ± 3.30	61.17 ± 9.21	61.35 ± 5.20
Percent body fat (%)					
Before	13.62 ± 5.14	14.02 ± 6.08	13.18 ± 3.07	10.00 ± 3.19	11.53 ± 6.45
After	14.20 ± 4.55	13.55 ± 6.33	11.88 ± 2.11	9.22 ± 3.55	10.46 ± 5.63
${}_{I}\text{VO}_{2\text{max}}$ (ml.kg.min^{-1})					
Before	40.33 ± 6.56	41.11 ± 2.35	41.55 ± 5.01	40.85 ± 4.13	39.67 ± 2.17
After	38.23 ± 4.35	46.90 ± 4.34	52.24 ± 2.88*	48.97 ± 1.72*	46.65 ± 5.45*
$T_{\text{Lim}}\text{VO}_{2\text{max}}$ (ml.kg.min^{-1})					
Before	39.11 ± 3.12	40.90 ± 4.21	43.67 ± 4.23	43.10 ± 4.02	41.77 ± 3.24
After	39.53 ± 2.37	44.00 ± 3.81	52.12 ± 2.95*	47.44 ± 2.05	46.44 ± 3.26*
BLC (mmol/L)					
Before	9.60 ± 3.33	9.82 ± 2.22	11.61 ± 2.71	9.35 ± 4.75	9.90 ± 1.79
After	7.45 ± 2.56	10.45 ± 2.56	13.90 ± 4.25*	10.20 ± 2.19	11.35 ± 4.35
HR (beat/min)					
Before	183.33 ± 9.80	178.28 ± 6.49	185.56 ± 4.45	184.50 ± 14.00	183.17 ± 6.86
After	181.39 ± 9.16	183.11 ± 7.48	183.83 ± 5.74	181.67 ± 7.39	185.06 ± 6.39
RPE					
Before	17.67 ± 1.75	18.00 ± 1.26	18.67 ± 1.37	17.33 ± 1.51	16.50 ± 1.52
After	16.83 ± 2.04	17.50 ± 1.22	18.00 ± 1.55	18.50 ± 0.84	16.67 ± 1.03

Note. BLC: blood lactate concentration; HR: heart rate; RPE: rate of perceived exertion. Pre- and post-training parameters for all groups (values are mean ± SD). Asterisks (*) significant change from pre- to post-training within the same group ($p < 0.05$).

Coefficient Confidence Intervals (ICC CI 95%) were determined to represent the proportion of variance in a set of scores that is attributable to the true score variance. All results were presented as the mean ± SD. GraphPad Software GraphPad Prism 6 was used for graphical expression. G Power (3.1.9.2) program was used in sample size calculation. The effect size was determined as $d = 1.9811$. Type I error level (α – error level) was set at 0.05 and Type II error (β) set at 0.20. The sample size was calculated as at least 5 participants for each group.

3. Results

3.1. Physical and physiological components

Data on the physical and physiological characteristics of participants are outlined in Table 1. No significant difference was traced in ${}_{I}\text{VO}_{2\text{max}}$ among groups in baseline measurements ($p = 0.42$). However, there was a significant improvement in ${}_{I}\text{VO}_{2\text{max}}$ in HIIT + NMES (41.55 ± 5.01 vs. 52.24 ± 2.88 ml.kg.min^{-1}, $p = 0.025$) and CA + NMES (39.67 ± 2.17 vs. 46.65 ± 5.45 ml.kg.min^{-1} $p = 0.028$) groups. $T_{\text{Lim}}\text{VO}_{2\text{max}}$ increased by 17.64% in HIIT + NMES and 10.59% in CA + NMES group. Significant difference ($p = 0.004$) was observed in $T_{\text{Lim}}\text{VO}_{2\text{max}}$ between HIIT + NMES (52.12 ± 2.95 ml.kg.min^{-1}) and CA + NMES (46.44 ± 3.26 ml.kg.min^{-1}) group in follow-up measurements. Peak blood lactate concentration was significantly different subsequent to ${}_{I}\text{VO}_{2\text{max}}$ and $\text{T}_{\text{Lim}}\text{VO}_{2\text{max}}$ in CA + NMES and HIIT + NMES groups compared to the control group in follow-up measurements (Table 1).

We found no statistically significant differences between baseline and post-test $\text{VO}_{2\text{max}}$ levels in Control (– 5.21%) and HIIT (14.08%) groups while HIIT + NMES (25.73%), CA (19.88%) and CA + NMES (17.60%) groups showed significant improvements in $\text{VO}_{2\text{max}}$ in this study. However, HIIT + NMES (19.35%) and CA + NMES (11.18%) training groups also showed significant increases in time to exhaustion performance at their ${}_{I}\text{VO}_{2\text{max}}$ after 8 weeks of training.

3.2. The peak moments

The baseline and post-test values of the PM in all groups are outlined in Table 2. No inter-group differences were noted in any of the baseline values. Both D and ND extension and flexion PMs were significantly higher in HIIT + NMES group at 60 and 180°/s

Table 2
Comparison of baseline and post-test isokinetic peak moment parameters among groups

Variable	Control ($n = 9$)	HIIT ($n = 9$)	HIIT + NMES ($n = 9$)	CA ($n = 9$)	CA + NMES ($n = 9$)
60°/s isokinetic knee extension (con) and flexion (con) peak moment strength parameters (Nm)					
D Ext. (Nm)					
Pre	270.43 ± 26.27	279.57 ± 44.65	298.67 ± 44.11	237.83 ± 21.76	264.67 ± 25.27
Post	248.77 ± 27.73	269.23 ± 65.65	310.21 ± 36.88*	231.69 ± 27.59	259.03 ± 21.59
%Dif.	−8.01	−3.70	3.86	−2.58	−1.88
ND Ext. (Nm)					
Pre	269.17 ± 18.57	253.50 ± 23.76	288.67 ± 34.61	233.50 ± 26.21	243.77 ± 18.27
Post	240.53 ± 35.82	260.43 ± 22.76	299.55 ± 28.54*	226.50 ± 36.86	245.13 ± 21.38
%Dif.	−10.64	2.73	3.77	−3.00	0.56
D Flex. (Nm)					
Pre	164.87 ± 11.47	153.45 ± 21.74	175.50 ± 12.05	137.01 ± 21.43	151.23 ± 21.78
Post	155.57 ± 10.68	158.67 ± 45.04	188.52 ± 25.23*	144.73 ± 11.22	154.73 ± 11.52
%Dif.	−5.64	3.40	7.42	5.63	2.31
ND Flex. (Nm)					
Pre	155.16 ± 22.25	157.80 ± 21.09	168.53 ± 15.35	124.11 ± 21.43	141.20 ± 21.80
Post	154.53 ± 17.89	158.50 ± 45.23	176.13 ± 21.40*	127.23 ± 15.38	139.27 ± 11.48
%Dif.	−0.41	0.44	4.51	2.51	−1.37
180°/s isokinetic knee extension (con) and flexion (ecc) peak moment strength parameters (Nm)					
D Ext. (Nm)					
Pre	160.83 ± 26.12	163.10 ± 30.21	157.17 ± 24.67	148.35 ± 22.35	158.86 ± 11.42
Post	159.10 ± 11.75	166.43 ± 31.17	178.81 ± 17.12*	151.00 ± 17.74	172.21 ± 12.47*
%Dif.	−1.08	2.04	13.77	1.79	8.40
ND Ext. (Nm)					
Pre	150.12 ± 11.13	161.55 ± 20.51	155.17 ± 15.41	138.36 ± 20.09	153.12 ± 20.21
Post	139.23 ± 21.75	168.10 ± 17.15	174.23 ± 21.10*	150.13 ± 12.57	171.18 ± 13.11*
%Dif.	−7.25	4.05	12.28	8.51	11.79
D Flex. (Nm)					
Pre	90.47 ± 11.63	93.52 ± 15.48	106.17 ± 17.52	89.66 ± 11.18	88.67 ± 11.78
Post	90.07 ± 12.35	96.81 ± 15.76	126.12 ± 11.26*	91.45 ± 11.26	98.17 ± 7.39*
%Dif.	−0.44	3.52	18.79	2.00	10.71
ND Flex. (Nm)					
Pre	86.10 ± 14.95	90.12 ± 11.35	101.32 ± 11.08	80.01 ± 20.76	81.00 ± 11.15
Post	85.27 ± 12.88	98.14 ± 13.26	125.67 ± 10.17*	87.35 ± 11.86	93.13 ± 18.20*
%Dif.	−0.96	8.90	24.03	9.17	14.98

Note. Ext: extension; Flex: flexion. * Significant value ($p < 0.05$). %Dif. stands for the percent increase between the baseline and follow-up measurements for the same variable.

group while CA + NMES training group displayed significant PM increases at 180°/s, whereas no differences were noted in HIIT and CA training alone (Table 2). Significant increases in the extension PM of the D (3.86%) and ND leg (3.77%) at 60°/s were observed from baseline to follow-up in HIIT + NMES group (Table 2). Significant increases in extension PM were also measured at 180°/s in the D leg (13.77%) and ND leg (12.28%) following the same intervention.

3.3. HQR and DCR

There were no significant differences in the HQR at 60°/s and the DCR at 180°/s for both the D (Table 3) and ND limb (Table 4) among groups at baseline. This changed into significant differences for both ratios, in both limbs in HIIT + NMES group. Additionally, DCR was found significantly increased for the D limb in CA + NMES group. Despite no statistical significance, ND DCR was higher compared to baseline measures in the CA + NMES group.

3.4. The correlations between the isokinetic ratios and VO$_{2max}$ parameters

The individual changes in D HQR were correlated with both the change in $_I\mathrm{VO}_{2\max}$ ($r = 0.94$, $p = 0.005$) and the change in T_{Lim} at $\mathrm{VO}_{2\max}$ ($r = 0.81$, $p = 0.050$). The results of correlation analysis also showed a positive significant correlation between the DCR, $_I\mathrm{VO}_{2\max}$ and T_{Lim} at $\mathrm{VO}_{2\max}$ ($r = 0.87$, $p = 0.019$; $r = 0.90$, $p = 0.015$) respectively. ND ratios were also positively correlated with $_I\mathrm{VO}_{2\max}$ and T_{Lim} at $\mathrm{VO}_{2\max}$ (Table 5).

Table 3
Baseline and post test mean and standard deviation of the DCR and HQR in D limb, expressed in %

	HQR_{60}					DCR_{180}				
	Pre H:Q	ICC	Post H:Q	ICC	p	Pre H:Q	ICC	Post H:Q	ICC	p
Control	60.97 ± 6.18	0.78	62.53 ± 5.08	0.81	0.92	56.25 ± 9.00	0.88	56.61 ± 7.89	0.86	0.50
HIIT	54.89 ± 7.39	0.83	58.93 ± 7.00	0.81	0.12	59.33 ± 12.08	0.90	58.17 ± 15.18	0.84	0.92
HIIT + NMES	58.76 ± 9.89	0.90	63.12 ± 10.86	0.92	0.03*	67.55 ± 15.36	0.91	70.53 ± 7.88	0.91	0.05*
CA	57.61 ± 8.98	0.89	62.47 ± 4.80	0.94	0.26	60.44 ± 8.38	0.93	60.56 ± 4.02	0.90	0.69
CA + NMES	57.14 ± 8.57	0.85	59.73 ± 6.81	0.90	0.23	55.82 ± 12.44	0.89	57.01 ± 8.80	0.85	0.04*

Note. * Significant value ($p < 0.05$). HIIT: High intensity interval training; CA: Continuous aerobic training; NMES: Neuromuscular electrical stimulation; ICC: Intraclass coefficient.

Table 4
Baseline and post test mean and standard deviation of the DCR and HQR in ND limb, expressed in %

	HQR_{60}					DCR_{180}				
	Pre H:Q	ICC	Post H:Q	ICC	p	Pre H:Q	ICC	Post H:Q	ICC	p
Control	62.27 ± 9.83	0.89	60.09 ± 3.01	0.90	0.12	57.35 ± 14.77	0.85	61.24 ± 6.10	0.88	0.35
HIIT	62.25 ± 12.61	0.83	60.86 ± 16.82	0.88	0.40	55.78 ± 19.20	0.87	58.38 ± 20.92	0.83	0.79
HIIT + NMES	57.64 ± 8.71	0.90	64.25 ± 9.18	0.89	0.01*	60.67 ± 11.99	0.90	65.30 ± 16.91	0.89	0.02*
CA	53.15 ± 9.67	0.78	56.17 ± 8.56	0.80	0.29	57.83 ± 13.92	0.89	58.18 ± 7.80	0.91	0.29
CA + NMES	57.92 ± 7.15	0.85	56.81 ± 9.93	0.78	0.60	52.90 ± 7.31	0.87	54.40 ± 13.26	0.89	0.60

Note. * Significant value ($p < 0.05$). ICC: Intraclass coefficient.

Table 5
Correlation values between post-test T_{Lim} at $VO_{2\text{max}}$ performance and H:Q ratios in the 60 and 180°/s angular velocities

Variable	${}_{I}VO_{2\text{max}}$-r (p)		$T_{\text{Lim}}VO_{2\text{max}}$ r (p)	
	Pre	Post	Pre	Post
D HQR_{60n}	0.32 (0.174)	0.94 (0.005)**	0.38 (0.271)	0.81 (0.050)*
ND HQR_{60}	0.42 (0.065)	0.88 (0.018)*	0.26 (0.258)	0.78 (0.015)*
D DCR_{180}	0.44 (0.100)	0.87 (0.019)*	0.32 (0.174)	0.90 (0.015)*
ND DCR_{180}	0.39 (0.186)	0.85 (0.011)*	0.32 (0.168)	0.87 (0.014)*

Note. * Significant value ($p < 0.05$); ** Significant value ($p < 0.001$). ${}_{I}VO_{2\text{max}}$: Intensity at $VO_{2\text{max}}$; $T_{\text{Lim}}VO_{2\text{max}}$: Time to exhaustion at ${}_{I}VO_{2\text{max}}$.

3.5. Isokinetic peak moment strength at different angular velocities

Intra-group comparisons of post-test values of the PMs revealed that HIIT + NMES group displayed significantly higher extension and flexion PM at both angular velocities compared to other groups. Intra-group comparisons revealed that HIIT + NMES group had significantly higher extension PM at 60°/s in the D leg compared to Control, CA, and CA + NMES groups. 60°/s extension PM in the ND leg was also significantly higher compared to CA and CA + NMES groups. Additionally, both D and ND leg extension and flexion PMs at 180°/s was found significantly greater compared to other groups (Table 6).

3.6. The associations between the isokinetic ratios and extension and flexion peak moments

The results of the Pearson product-moment correlation coefficient analysis revealed significant positive correlations between DCR and knee flexion moment at both D ($r = 0.65$, $p = 0.021$) and ND limb ($r = 0.65$, $p = 0.033$). Additionally, there was a negative significant correlation between DCR and knee extension moment at both 60°/s ($r = -0.49$, $p = 0.025$) and 180°/s ($r = -0.62$, $p = 0.015$), respectively (Table 7).

4. Discussion

The tendency to a limb dominance or preference associated with a functional movement repetitiveness in many sports stimulates muscular imbalances of strength [31]. During cycling, the proportion of power acquired by the activation of quadriceps muscle activity has been described as typically more dominant than hamstring muscles [32,33]. In this regard, a relative overuse of the quadriceps muscle-tendon unit has been reported to lead an increase in compressive forces at the anterior knee and, the hamstrings play a more

Table 6
Intra-group comparisons of post-test 60°/s and 180 °/s isokinetic strength parameters following 8 weeks of training

Groups	Mean ± SD	P value
Concentric mode 60°/sec		
D Extension (Nm)		
HIIT + NMES vs. Control	310.21 ± 36.88 vs. 248.77 ± 27.73	0.003**
HIIT + NMES vs. CA + NMES	310.21 ± 36.88 vs. 259.03 ± 21.59	0.006**
HIIT + NMES vs. CA	310.21 ± 36.88 vs. 231.69 ± 27.59	0.016*
ND Extension (Nm)		
HIIT + NMES vs. CA + NMES	299.55 ± 28.54 vs. 245.13 ± 21.38	0.010*
HIIT + NMES vs. CA	299.55 ± 28.54 vs. 226.50 ± 36.86	0.025*
Eccentric mode 180°/sec		
D Extension (Nm)		
HIIT + NMES vs. CA	178.81 ± 17.12 vs. 151.00 ± 17.74	0.008**
HIIT + NMES vs. CA + NMES	178.81 ± 17.12 vs. 172.21 ± 12.47	0.037*
ND Extension (Nm)		
HIIT + NMES vs. Control	174.23 ± 21.10 vs. 139.23 ± 21.75	0.016*
HIIT + NMES vs. CA	174.23 ± 21.10 vs. 150.13 ± 12.57	0.004**
HIIT + NMES vs. CA + NMES	174.23 ± 21.10 vs. 171.18 ± 13.11	0.025*
D Flexion (Nm)		
HIIT + NMES vs. Control	126.12 ± 11.26 vs. 90.07 ± 12.85	0.002**
HIIT + NMES vs. HIIT	126.12 ± 11.26 vs. 96.81 ± 15.76	0.003**
HIIT + NMES vs. CA	126.12 ± 11.26 vs. 91.45 ± 11.26	0.002**
HIIT + NMES vs. CA + NMES	126.12 ± 11.26 vs. 93.13 ± 18.20	0.001**
ND Flexion (Nm)		
HIIT + NMES vs. Control	125.67 ± 10.17 vs. 85.27 ± 12.88	0.010**
HIIT + NMES vs. CA	125.67 ± 10.17 vs. 87.35 ± 11.86	0.005**
HIIT + NMES vs. CA + NMES	125.67 ± 10.17 vs. 93.13 ± 18.20	0.010*

Note. Asteriks (*) and (**) indicate statistically significant difference between two groups at a significance level of $p < 0.05$ and $p < 0.001$ level between two groups.

Table 7
Correlations among knee extension and flexion PMs, DCR and HQR

Variable	DCR-r (p)		HQR r (p)	
	Pre	Post	Pre	Post
60°/s D Extension (Nm)	−0.21 (0.181)	−0.25 (0.212)	−0.33 (0.203)	−0.49 (0.025)*
180 °/s D Extension (Nm)	−0.30 (0.205)	−0.35 (0.125)	−0.40 (0.155)	−0.62 (0.015)*
180 °/s D Flexion (Nm)	0.28 (0.121)	0.65 (0.021)*	0.43 (0.161)	0.44 (0.135)
180 °/s ND Flexion (Nm)	0.32 (0.105)	0.65 (0.033)*	0.41 (0.147)	0.46 (0.151)

Note. *Significant value ($p < 0.05$). PMs: Peak moment strength, DCR: Dynamic control ratio, HQR: Hamstring/Quadriceps ratio.

coordinative role during pedal stroke [34] if repeated muscle activations are performed for long periods with high intensity.

Since cycling involves the interactions of neuromuscular, aerobic and anaerobic components, it is essential to understand the determinants underlying endurance cycling performance. It has been reported in a recent study that eccentric training (with or without NMES) did not affect concentric peak moment and vastus lateralis pennation angle but improved eccentric (13%) peak moment [35]. In the current study, we found significant increases in strength parameters both in HIIT + NMES and CA + NMES training groups but not in HIIT and CA training alone (Table 2). Our results showed that contrary to HIIT + NMES training group, neither CA with/without NMES nor variable power HIIT cycling training without NMES have resulted in a significant increase of peak moment strength of the knee extensor muscles at 60°/s. Similarly, another study reported that the strength loss in knee extensor muscles resulted from central and peripheral mechanisms after cycling was similar for the constant and the variable power output protocols [36]. An interesting finding in our study is that the highest eccentric and concentric strength increases were only seen in HIIT + NMES group at both velocities which was also the only group that showed significant improvements in D (Table 3) and ND (Table 4) DCR and HQR from baseline to post-test measurements. When the changes in the muscle contraction patterns of the lower extremity muscles in all groups are taken into consideration, the highest eccentric muscle strength gain was also found in HIIT + NMES group at 60°/s (7.42%) and 180°/s (24.3%) (Table 2). In the current study, to investigate the effect of NMES on muscular activity during $\mathrm{VO_{2max}}$ testing, correlation analysis was performed between the HQR and DCR of the same muscle. Significant correlations were found among $\mathrm{T_{Lim}VO_{2max}}$, $_I\mathrm{VO_{2max}}$, HQR and, DCR following 8 weeks of training (Table 5). However, correlations between the DCR and $\mathrm{T_{Lim}VO_{2max}}$ were found to be superior both in D and ND limb compared to those that occurred between the HQR and $\mathrm{T_{Lim}VO_{2max}}$. These results suggest that the low-energy expenditure may partly be related to the higher DCRs of the subjects' hamstring muscles but not to the absolute strength. Additionally, the results of the current study showed a positive significant correlation between the DCR and knee flexion strength of both D and ND limb ($r = 0.65$), and negative significant correlation between the DCR and isokinetic knee extension strength at 60°/s ($r = -0.49$) and 180°/s ($r = -0.62$), respectively (Table 7). These results suggest that it is essential to enhance eccentric hamstring muscle strength more than quadriceps to increase DCR and the evaluation of the DCR may yield useful information to screen the actual muscular performance of lower limbs during cycling $\mathrm{VO_{2max}}$ testing compared to the HQR.

To date, only one study reported that the combined application of aerobic cycling exercise and resistance through an electrically stimulated antagonist could result in increased $\mathrm{VO_2}$ by about 20% with a linear relationship to workload in comparison to aerobic cycling exercise alone [37]. The reported results were in accordance with the results of our study in terms of $\mathrm{VO_2}$ increases. We found an increase in $\mathrm{VO_2}$ parameters by about 25.73% following HIIT + NMES training. Additionally, the highest increase in time to exhaustion performed at maximal individual fatigue intolerance point was also seen in HIIT + NMES group. Also, peak blood lactate concentration was found significantly increased in HIIT + NMES (19.72%) compared to other groups in our study (Table 1). Previous studies on the thigh muscles during cycling have shown that the force generation has been attributed predominantly to the mono-articular muscles such as biceps femoris, vastus lateralis and vastus medialis during the propulsion phase while bi-articular muscles such as rectus femoris, SemM, and SemT assist in directing the pedal forces and redistributing net moments over the joints during pedal cycle [38]. Also, noted that the co-activation between knee extensors and flexors during the propulsion phase of pedaling has been suggested to regulate the net joint moments responsible for force transfer to the pedal [39]. Thus, the application of NMES stimuli on these specific muscle groups coupled with HIIT in the current study appears to increase neuromuscular performance, and energy expenditure attributed by both aerobic and anaerobic metabolism since HIIT training is performed at a very high respiratory quotient. The previous data noted that NMES increases localized blood flow [40,41]. Thus, although direct blood flow was not measured in our study, significant improvements in time to exhaustion performance in HIIT + NMES group indicate that NMES may have affected localized blood flow of quadriceps muscles and increased metabolite removal from the fatigued muscles. Or it could have increased the efflux of contraction-induced metabolites from the stimulated muscle mass owing to its role on muscle-pump, analgesic effects on muscle soreness and lymphatic drainage to the stimulated area. Similar to our findings, the NMES implementation has been reported to enhance a significant improvement in the maximal voluntary contraction of the quadriceps muscle [42] since the contractions of leg muscles stimulates leg muscle venous pump activity, increasing venous return, stroke volume, and cardiac output during high-intensity exercises. The significant improvements observed both in neuromuscular and cardiorespiratory components in HIIT + NMES in the current study suggest that NMES proportionally increases aero-metabolic capacity, prevention of muscle atrophy, and increases resistance to fatigue during intense exercises increasing capillary density, mitochondrial concentrations, and oxidative enzyme levels, associated with the transformation of muscle fibers. Additionally, the increases in eccentric muscle contraction and DCR following HIIT + NMES seem to improve fatigue tolerance, cause less fatigue and oxidative stress on the lower limb during pedaling at high intensities.

Despite the differences in muscle contraction patterns between cycling and running, another study reported that DCR at 180°/s was significantly correlated with sub-maximal $\mathrm{VO_2}$ at 201.2 $\mathrm{m{\cdot}min^{-1}}$, suggesting that strong knee flexion may be important for running at low oxygen cost [33]. However, neither absolute knee extensor nor knee flexor moment was found to be significantly correlated with the running economy. Nevertheless, since the medial hamstring muscles were reported to recruit together with quadriceps muscles, and all these muscles became a synergistic group during pedaling [43] storage of elastic energy in the contracted muscle during eccentric muscle actions is an important mediator to increase the total work output during muscle contractions. It was indicated in another study that the higher DCR values in highly trained runners could be explained by their increased eccentric strength due to the larger elasticity and stiffness which affected the eccentric hamstring moment [44]. In terms of limitations of this study, the small sample size, the exclusive gender set-up and only two angular velocities may restrict its generalizability. In particular, the DCR was derived from the same angular speed 180°/s, unlike in some previous studies. This latter factor in conjunction with the noncompatibility of certain isokinetic dynamometers require extra caution in interpretation of the findings. Future studies may consider variations on these parameters, most importantly, the inclusion of women.

5. Conclusion

This study highlights the influences of NMES on muscular, aerobic and, anaerobic cycling exercise performance, and also indicates that NMES may serve as a complementary training tool to improve aerobic and anaerobic cycling performance. In the lights of these findings, it is important to improve strength values between agonist and antagonist muscles symmetrically to modulate functionality and the articular biomechanics of the knee during these repetitive movements. It may also be speculated that compared to concentric contractions the presence of an eccentric component may be more beneficial, more efficient from the neuromuscular point of view and less metabolically demanding during endurance cycling. To this end, early emphasis should be on hamstrings and coaches and athletes may focus on eccentric hamstring muscle actions to increase DCR. Additionally, DCR provides a good estimation of the co-activation of the flexors and extensors. It can also help to identify potential muscular imbalances which are crucial for endurance cycling performance. Besides, conventional HQR may not yield useful information to precisely evaluate the breaking function of the hamstrings during an extension of maximal quadriceps strength. On the other hand, if the athletes have quadriceps hypertrophy or a unilateral strength discrepancy between quadriceps and hamstring muscles (attributable to a greater inhibitory effect on the ability to co-activate knee flexors during high-intensity cycling), the ratio of hamstring to quadriceps strength might have a negative impact on all-out cycling performance if this discrepancy is not rectified.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

[1] Croisier JL, Ganteaume S, Binet J, Genty M, Ferret JM. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. Am J Sports Med. 2008; 36(8): 1469-1475.

[2] D'Onofrio R, Tamburrino P, Manzi V, Tucciarone A, Tavana R, Bhatt, J, Training neuromuscolari in età pediatrica. Valutazione della letteratura per un corretto protocollo applicativo nella prevenzione delle lesioni del LCA in soggetti scheletricamente immaturi. Ita J Sports Reh Po. 2018; 5(2): 990-1012.

[3] Cheung R, Smith A, Wong D. H:Q ratios and bilateral leg strength in college field and court sports players. Journal of Human Kinetics. 2012; 33(1): 63-71.

[4] Daneshjoo A, Rahnama N, Mokhtar AH, Yusof A. Bilateral and unilateral asymmetries of isokinetic strength and flexibility in male young professional soccer players. Journal of Human Kinetics. 2013; 36(1): 45-53.

[5] Dervišević E, Hadžić V. Quadriceps and hamstrings strength in team sports: basketball, football and volleyball. Isokinetics and Exercise Science. 2012; 20(4): 293-300.

[6] Hewett TE, Myer GD, Zazulak BT. Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. Journal of Science and Medicine in Sport. 2008; 11(5): 452-459.

[7] Kim D, Hong J. Hamstring to quadriceps strength ratio and noncontact leg injuries: a prospective study during one season. Isokinetics and Exercise Science. 2011; 19(1): 1-6.

[8] Li L. Neuromuscular control and coordination during cycling. Res Q Exerc Sport. 2004; 75: 16-22.

[9] Figueiredo P, Zamparo P, Sousa A, Vilas-Boas JP, Fernandes RJ. An energy balance of the 200 m front crawl race. Eur J Appl Physiol. 2011; 111(5): 767-77.

[10] Fernandes RJ, Vilas-Boas JP. Time to exhaustion at the VO2max velocity in swimming: A review. J Hum Kinet. 2012; 32: 121-134.

[11] Mujika I, Rønnestad BR, Martin DT. Effects of increased muscle strength and muscle mass on endurance-cycling performance. Int J Sports Physiol Perform. 2016; 11(3): 283-9.

[12] Farrell KC, Reisinger KD, Tillman MD. Force and repetition in cycling: possible implications for iliotibial band friction syndrome. The Knee. 2003; 10(1): 103-109.

[13] Lepers R, Hausswirth C, Maffiuletti N, Brisswalter J. Evidence of neuromuscular fatigue following prolonged cycling exercise. Med Sci Sport Exerc. 2000; 32: 1880-1886.

[14] Lepers R, Millet GY, Maffiuletti N. Effect of cycling cadence on contractile and neural properties of knee extensors. Med Sci Sports Exerc. 2001; 33: 1882-1888.

[15] Lepers R, Maffiuletti N, Rochette L, Brugniaux J, Millet GY. Neuromuscular fatigue during a long duration cycling exercise. J Appl Physiol. 2002; 92: 1487-1493.

[16] Porcari JP, Ryskey A, Foster C. The effects of high intensity neuromuscular electrical stimulation on abdominal strength and endurance, core strength, abdominal girth, and perceived body shape and satisfaction. International Journal of Kinesiology and Sports Science. 2018:; 6(1): 19.

[17] Caulfield B, Prendergast A, Rainsford G, Minogue C. Self-directed home based electrical muscle stimulation training improves exercise tolerance and strength in healthy elderly. Conf Proc IEEE Eng Med Biol Soc. 2013; 7036-9.

[18] Banerjee P, Caulfield B, Crowe L, Clark A. Prolonged electrical muscle stimulation exercise improves strength and aerobic capacity in healthy sedentary adults. J Appl Physiol. 2005; 99(6): 2307-2311.

[19] Dehail P, Duclos C, Barat M. Electrical stimulation and muscle strengthening. Ann Readapt Med Phys. 2008; 51: 441-451.

[20] Paillard T. Combined application of neuromuscular electrical stimulation and voluntary muscular contractions. Sports Med. 2008; 38: 161-177.

[21] Jones AM, Carter H. The effect of endurance training on parameters of aerobic fitness. Sports Med. 2000; 29: 373-386.

[22] Metcalfe RS, Babraj JA, Fawkner SG, Vollaard NB. Towards the minimal amount of exercise for improving metabolic health: beneficial effects of reduced-exertion high-intensity interval training. Eur J Appl Physiol. 2012; 112: 2767-2775.

[23] Murias JM, Kowalchuk JM, Paterson DH. Speeding of VO2 kinetics with endurance training in old and young men is associated with improved matching of local O2 delivery to muscle O2 utilization. J Appl Physiol. 2010; 108: 913-922.

[24] Nelson ME, Rejeski WJ, Blair SN, Duncan PW, Judge JO, et al. American College of Sports Medicine; American Heart Association, Physical activity and public health in older adults: recommendation from the American College of Sports Medicine and the American Heart Association. Circulation. 2007; 116: 1094-105.

[25] Zhou S, McKenna MJ, Lawson DL, Morrison WE, Fairweather I. Effects of fatigue and sprint training on electromechanical delay of knee extensor muscles. Eur J Appl Physiol Occup Physiol. 1996; 72: 410-416.

[26] Macaluso A, Young A, Gibb KS, Rowe DA, De Vito G. Cycling as a novel approach to resistance training increases muscle strength, power, and selected functional abilities in healthy older women. J Appl Physiol. 2003; 95: 2544-2553.

[27] Dick R, Hertel J, Agel J, Grossman J, Marshall SW. Descriptive epidemiology of injuries players students: National Student Athletic Association surveillance scheme injuries, 1988–1989 through 2003–2004. J Athl Train. 2007; (42): 194-201.

[28] Carvalho HM, Coelho ESMJ, Ronque ER, Goncalves RS, Philippaerts RM, Malina RM, Evaluation of reliability of isokinetic testing among adolescents basketball, Medicina. 2011; (47): 446-452.

[29] Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Bojsen-Moller F, Dyhre-Poulsen P. Antagonist muscle coactivation during isokinetic knee extension. Scand J Med. 2000; (10): 58-67.

[30] Tourny-Chollet C, Leroy D. Conventional vs. dynamic hamstring-quadriceps strength ratios: A comparison between players and sedentary subjects. Isokinetics and Exercise Science. 2002; (10): 183-192.

[31] Pinto MD. Hamstring-to-quadriceps fatigue ratio offers new and different muscle function information than the conventional non-fatigued ratio. Scand J Med Sci Sport. 2018; 28(1): 282-293.

[32] Camic CL, Kovacs AJ, Enquist EA, McLain TA, Hill EC. Muscle activation of the quadriceps and hamstrings during incremental running. Muscle & Nerve. 2015; 52(6): 1023-1029.

[33] Sundby QH, Gorelick M. Relationship between functional hamstring: quadriceps ratios and running economy in highly trained and recreational female runners. Journal of Strength and Conditioning Research. 2014; 28(8): 2214-27.

[34] Blake OM, Champoux Y, Wakeling JM. Muscle coordination patterns for efficient cycling. Med Sci Sports Exerc. 2012; 44: 926-938.

[35] da Silva CFC, Felipe E, Silva XL, Vianna KB, Oliveira GDS, Vaz MA, Baroni BM. Eccentric training combined to neuromuscular electrical stimulation is not superior to eccentric training alone for quadriceps strengthening in healthy subjects: A randomized controlled trial. Braz J Phys Ther. 2018; 22(6): 502-511.

[36] Lepers R, Theurela J, Hausswirth C, Bernard T. Neuromuscular fatigue following constant versus variable-intensity endurance cycling in triathletes. Journal of Science and Medicine in Sport. 2008; (11): 4, 381-389.

[37] Masayuki O, Matsuse H, Takano Y, Yamada S, Ohshima H, et al. Oxygen uptake during aerobic cycling exercise simultaneously combined with neuromuscular electrical stimulation of antagonists. J Nov Physiother. 2013; 3: 185.

[38] Dorel S, Couturier A, Hug F. Intra-session repeatability of lower limb muscles activation pattern during pedaling. J Electromyogr Kinesiol. 2008; 18: 857-865.

[39] Hug F, Turpin NA, Couturier A, Dorel S. Consistency of muscle synergies during pedaling across different mechanical constraints. J Neurophysiol. 2011; 106: 91-103.

[40] McLoughlin TJ, Snyder AR, Brolinson PG, Pizza FX. Sensory level electrical muscle stimulation: effect on markers of muscle injury. Br J Sports Med. 2004; 38(6): 725-729.

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

[42] Vivodtzev I, Pepin JL, Vottero G, Mayer V, Porsin B, Levy P, Wuyam B. Improvement in quadriceps strength and dyspnea in daily tasks after 1 month of electrical stimulation in severely deconditioned and malnourished COPD. Chest. 2006; 129: 1540-1548.

[43] da Silva JCL, Tarassova O, Ekblom MM, Andersson E, Rönquist G, Arndt A. Quadriceps and hamstring muscle activity during cycling as measured with intramuscular electromyography. Eur J Appl Physiol. 2016; 116: 1807-1817.

[44] Bojsen-Møller J, Magnusson SP, Rasmussen LR, Kjaer M, Aagaard P. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. J Appl Physiol. 2005; 99: 986-994.