

Research Article

Running economy and metabolic responses following exercise-induced muscle damage at two different velocities

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Abstract

Eccentric contractions predispose muscles to damage. Type II muscle fibers are more susceptible than type I, so it seems that contraction velocity interferes in mechanical stress and thus muscle damage. The purpose of this study was to investigate the effect of contraction velocity of acute dominant knee extensor eccentric exercise-induced muscle damage (EIMD) on running economy and metabolic responses in trained young females. Twenty-one trained young females were randomly assigned into two groups: high-velocity contraction eccentric exercise (240°s⁻¹) and low-velocity (60°s⁻¹). To induce muscle damage subjects, in high and low-velocity groups performed 20 and 5 sets of 15 repetitions, respectively, with a load equal to 150% of the maximal voluntary isometric contraction (MVIC) torque of knee extensors with a dominant limb. Then; MVIC of knee extensors was recorded before, one and 48 h after EIMD, and running economy (submaximal Steady-state vo₂), and metabolic responses were recorded at 60, 70, and 80% of pre-determined vVO₂max, 24 h before and 48 h after EIMD. Both exercise bouts resulted in significant changes in MVIC of knee extensor (p<0.05) with no significant difference between the two groups. No significant difference was found in running economy and metabolic responses in three different intensities following both exercise conditions between the two groups. Results of the analysis showed that a four-fold difference in contraction velocity of eccentric exercise-induced muscle damage was not sufficient to induce a difference in muscle damage, running economy, and metabolic responses when the knee extensor muscle tension duration was equalized.

Key Words: EIMD, Contraction velocity, Running economy, Metabolic responses, Trained female

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Introduction

Eccentric exercises, which actively produce force while lengthening muscle fibers, are widely used in exercise training programs because the potential for producing force is high and the metabolic cost is lower (Hedayatpour & Falla, 2015). When this type of training is accompanied by overload, it is an effective stimulus to improve the growth and nerve conduction of the muscle (Hedayatpour & Falla, 2015). However, one of the main causes of temporary destructive changes in the ultra-structural part of the muscle and micro-injury in the muscle fibers is a result of performing these types of exercises, especially when the eccentric activity performed is new or unusual or the intensity and duration of training is high (Byrne et al., 2004). Following EIMD, structural changes at the cellular level contain damage to myofibrils and Z-line streaming, membrane damage with disruption of the T-tubule system and sarcoplasmic reticulum, disrupted cytoskeletal organization, in addition to changes in the function of glucose transport proteins, followed by changes in substrate levels (Stožer et al., 2020).

Depletion of glycogen reserves caused by metabolic stress leads to ATP deficiency and a decrease in the function of sarcoplasmic reticulum or sarcoplasmic reticulum ATPase. This leads to the activation of calcium-dependent proteolytic and phosphorylation pathways, which is thought to lead to the disruption of cytoplasmic proteins and membranes, converging with the mechanical stress pathway (Tee et al., 2007). Elsewhere, the clinical consequences of EIMD include reduced force production due to the reduction of contractile components, Excitation-contraction coupling failure, uncontrolled Ca²⁺ entry into the sarcoplasm, raising of passive tension, soreness, inflammation, stiffness, pain, and reduction of the range of motion (Bandyopadhyay, 2017). Nerve responses in injured muscles can also be impaired by the presence of pain, restructuring of neuromuscular junction, and altered proprioception (Hedayatpour & Falla, 2014). Even though these side effects die down within a week, they influence the athlete's training program and as a result, more vulnerable to sports injury (Allen et al., 2005). The occurrence of these symptoms is

more pronounced during periods of overtraining in athletes, and decreased muscle function can lead to decreased exercise performance and cause stress problems for athletes (Byrne et al., 2004). Less is known about endurance indicators after EIMD exposure compared to strength and power.

An important predictor of running endurance performance is running economy, which is defined as energy expenditure at a given sub-maximal speed (Lucia et al., 2006). This key indicator is more accurate than the maximum oxygen consumption (VO_{2max}) (Saunders et al., 2004) and a runner who can consume less oxygen while running at a certain speed has a better running economy (Barnes & Kilding, 2015). It has also been shown that neuromuscular control is impaired during submaximal contractions following EIMD (Plattner et al., 2011). Therefore, it seems that the running economy can also be affected by EIMD. The results of research in the field of running economy following EIMD are contradictory due to the use of different injury protocols and running economy evaluation methods. Several studies suggest that EIMD does not affect the running economy (Satkunskiene et al., 2015; Vassilis et al., 2008). In contrast, some studies have reported decreased running economy after this type of exercise (Burnett et al., 2010; Burnett et al., 2013).

In general, mechanical events are the main cause of muscle damage, and type II fibers appear to be more susceptible to muscle damage than type I fibers (Choi, 2014). Therefore, in addition to the intensity and number of repetitions, the contraction velocity as a mechanical factor may also affect the extent of muscle injury and thus the functional impact of the injury. To our knowledge, no studies to date have examined the effect of eccentric EIMD contraction velocity on running economy and metabolic responses. This study aimed to evaluate the effectiveness of the contraction velocity of acute eccentric EIMD of the knee extensor muscle on running economy and metabolic responses in trained young females.

Materials and Methods

Subjects

The present study was a quasi-experimental study with between-group repeated measures and pre-test and post-test design. A total of 21 trained young females were selected to participate in the study. Exclusion criteria included a history of lower extremity injury in the last 6 months such as fractures, ligament injuries to the knee, patellar tendinopathy, neuromusculoskeletal disorders, as well as the use of dietary supplements at least 3 months before and during the study, and doing eccentric or isokinetic strengthening training in the lower extremities at least 6 months before the study period.

Ethical approval was obtained from the Shiraz University of Medical Sciences ethics and research committee (IR.SUMS.REC.1395.146), and all participants signed a written informed consent before participation. They were randomly assigned into two groups, high-velocity eccentric contraction (HVEC) and low-velocity eccentric contraction (LVEC). The demographic characteristics of the subjects are shown in Table 1. The subjects' dominant leg was determined before the start of the exercise protocol. The subjects were asked to refrain from any strenuous exercise 48 hours before and during the test, not take anti-inflammatory drugs and dietary supplements, and avoid any treatment, including massage, cold therapy, pressure, etc., during the study.

Induction of muscle damage

After previous familiarization with an isokinetic dynamometer (Biodex System 4pro, Biodex Medical Systems, Inc., Shirley, NY, USA) for the measurement MVIC torque of knee extensors, the exercise protocol to induce muscle damage to the quadriceps muscle was performed. It consisted of 75 contractions (5 sets of 15 repetitions) in the low-velocity group and 300 contractions (20 sets of 15 repetitions) in the high-velocity group at a target of 150 % of the MVIC torque. The standard Biodex knee unit attachment was used to restrain the chest, pelvis, thigh, and ankle following the manufacturer's instructions. The resistance pad was placed as distally as possible on the tibia while still allowing full dorsiflexion of the ankle. The input axis of the dynamometer was aligned with the axis of the dominant knee.

Table 1. Demographic characteristics of the subjects by research groups

Group	Number	Demographic characteristics of the subjects				
		Indicator	Age (Year)	Height (cm)	Weight (kg)	BMI (kg/m ²)
High velocity	10		21.9±1.66	162.71±5.68	54.39±7.08	20.6±3.16
Low-velocity	11		21.72±1.27	161.77±5.63	58.02±7.23	22.13±2.16
Means comparison		t	0.269	0.379	-1.15	-1.30
		P-value	0.791	0.709	0.261	0.209

The subjects were instructed to perform an eccentric quadriceps contraction against the moving lever of the system at 60° and 240° per second in low and high-velocity groups respectively, using visual feedback from the dynamometer software as a means to maintain the strength intensity. The range of motion was set between 10 and 90° of the knee flexion (full extension equivalent to zero degrees).

The initial position was a 90-degree flexion, which completely relaxed the lower limb as the person began to move, and raised the device to 10 degrees of flexion (passive extension at a velocity of 300 degrees per second). Then, with starting the return movement in the direction of flexion, the subject was asked to resist maximally against the motion and maintain this resistance throughout the full range of the movement (90 degrees of flexion), which was equivalent to eccentric contraction of the knee extensors. During the exercise protocol, the subjects were encouraged to apply maximum force at each repetition. The resting time between sets was set at 60 seconds.

Maximum oxygen consumption (Vo2max)

To measure maximum oxygen consumption (Vo2max), a respiratory gas analyzer (German Cortex-Metalyzer 3B gas analyzer) and a treadmill (h / p / cosmos) were used. The Vo2max measurement protocol comprised one minute of active rest at 0.5 km / h, 2 minutes of warm-up at 5 km / h, followed by running at 7 km / h and increasing 1 km / h every minute until it reached exhaustion (Beltrami et al., 2012). Also, achieving the predicted maximum heart rate based on age (5% of age -220) and a respiratory exchange ratio of more than 1.15 (Harrison, 2009) were the criteria for Vo2max occurrence in this study. After the end of the test, the maximum oxygen consumption for each subject was determined. vVo2max was the velocity at which the person reached Vo2max and could maintain that velocity for at least 1 minute. Otherwise, the velocity of the previous step would be considered vVo2max (Hanson et al., 2011). This velocity was considered the maximum aerobic capacity of each individual (Di Michele, 2008).

Running economy and metabolic responses

Running economy and metabolic responses (co2, minute ventilation, respiratory exchange rate, heart rate) were evaluated 24 h before and 48 h after EIMD. The protocol for evaluation of running economy consisted of running on a treadmill in three submaximal stages, each one lasting for three minutes (trehearn & Buresh, 2009) at an intensity of 60, 70, and 80% of predetermined vo2maX (di Michele, 2008) and a 1-minute rest between each stage (Santos-concert et al., 2013) as walking at 0.5 km / h. The treadmill incline was 1% in all stages (Jones & Doust, 1996). During the testing stages, breath gases were continuously collected breath to breathe, and the running econo-

-my and metabolic responses were obtained with an average of the last 1 minute of each stage. Heart rate was also continuously recorded by fastening the sensor belt (Polar RS800, Kempele, Finland) around the subjects' chests. The lab temperature was almost kept constant during the testing process, the subjects were asked to use fixed shoes in each test session (Vassilis et al., 2008).

Indirect indicators of muscle damage

MVIC torque of the dominant knee extensor was measured one hour before (to reduce fatigue (Hicks et al., 2016) and 48 hours after the EIMD at three angles (30, 60, and 90 degrees of knee flexion). The subjects were asked to repeat the MVIC at each angle three times and the highest value was recorded (Vassilis et al., 2008). The duration of each test was 5 seconds, with 30 seconds of rest time between repetitions seconds (Rezaei et al., 2014). Visual feedback and verbal encouragement were used to increase the level of contraction force during the test.

Statistical analysis

Data analysis was performed by SPSS software (version 19). After examining the normal distribution, between-subject repeated-measures ANOVA was used to compare the two contraction velocities (high and low velocities) three times (before, one hour, and 48 hours after EIMD) on the MVIC torque of the dominant knee extensor at three angles of 30, 60, and 90 degrees. To compare the effect of two contraction velocities (high and low -velocities) at two times (24 hours before and 48 hours after the EIMD) on the running economy, the independent samples t-test and one-way analysis of covariance were used. The level of significance was set at $\alpha = 0.05$

Results

Indirect indicators of exercise-induced muscle damage

According to Tables 2 and 3, the results of between-group repeated-measures analysis of variance show that in the HVEC group, one hour after the eccentric exercise, the MVIC torque of the dominant knee extensor at three angles of 30, 60, and 90 degrees and 48 hours after exercise only at an angle of 60° flexion were significantly reduced relative to Baseline values. Also, in the HVEC group at a 30° angle, the isometric torque increased significantly 48 hours after exercise compared to one hour after exercise, however, it was lower than the baseline. In the LVEC group, one hour after the eccentric exercise, the MVIC torque of the dominant knee extensor at three angles 30, 60, and

Table 2. Changes in MVIC extensor torque from the Pre-exercise level to one and 48 hours after EIMD for the high and low velocity conditions.

Maximal voluntary isometric torque of the dominant knee extensor				
Group	Time	30° angle	60° angle	90° angle
High velocity	Before	66.41±11.10	116.41±15.25	136.92±17.71
	One hour after	38.14±11.06*	81.07±17.11*	112.95±25.63*
	48 hour after	56.46±11.73#	94.46±15.81*	123.06±16.74
	Effect size	0.77	0.56	0.36
Low -velocity	Before	74.32±17.51	122.07±28.81	148.01±23.92
	One hour after	47.75±14.01*	95.96±21.55*	119.87±32.07*
	48 hours after	59.15±19.69	103.78±28.37*	115.50±21.96*
	Effect size	0.57	0.54	0.55

* Significant difference compared to before acute eccentric EIMD # Significant difference compared to one hour after acute eccentric EIMD

Table 3. Pairwise comparison of the means of the MVIC torque of the dominant knee extensor in two groups, before, one hour and 48 hours after EIMD.

Mean differences (p-value)				
Group	Time	30° angle	60° angle	90° angle
High velocity	Before-One hour after	28.27 (<0.0001*)	35.34 (0.005*)	23.97 ((0.011*)
	Before-48 hours after	9.95 (0.152)	21.95 (0.048*)	13.86 (0.37)
	One hour after-48 hours after	-18.32 (<0.0001*)	-13.39 (0.22)	-10.11 (0.69)
Low velocity	Before-One hour after	26.57 (<0.001*)	26.10 (0.005*)	28.13 ((0.011*)
	Before-48 hours after	15.17 (0.062)	18.29 (0.009*)	32.50 (0.007*)
	One hour after-48 hours after	-11.40 (0.088)	-7.81 (0.55)	4.37 (1.000)

ees of the knee flexion was significantly reduced compared to the pre-exercise value. No significant difference in MVIC torque in 3 conditions (pre, 1-hour post-exercise, and 48 h post-exercise) was evident between the two groups (Table 4).

Running economy and metabolic responses

The mean, and standard deviation of running economy (submaximal steady-state relative oxygen consumption), and metabolic responses (carbon dioxide, minute ventilation, respiratory exchange ratio, heart rate) in three intensities of 60, 70, and 80% of the maximum oxygen consumption velocity is shown in the HVEC, and LVEC groups are shown in Table 5. Considering the results of Table 5, and the non-significance of the variables mentioned in the pre-test (P >0.05), the results of the post-test of the independent t-test also showed that the runni-

ng economy and metabolic responses did not differ significantly between the two groups (P >0.05).

Discussion

Typically, it was found that a single session of acute eccentric EIMD at two different velocities (high and low) with an intensity of 150% of the MVIC torque led to decrease MVIC torque in the dominant knee extensor muscle, which indicates muscle damage occurred in both groups. However, changes in MVIC torque in the high-velocity group compared to the low-velocity group were not significant over the three periods. An excessive increase in intracellular calcium following eccentric EIMD leads to the activation of proteolytic processes in the damaged muscle, which causes the destruction of contractile & non-contractile structures

Table 4. Repeated-measures analysis of variance of the maximal voluntary isometric torque of the dominant knee extensor at angles of 30, 60, and 90 degrees of the knee flexion.

Angle	Source	SS (Type III)	Degree of freedom	F	P-value	Effect size (Eta)
30°	Time	7895.82	2	36.94	<0.0001*	0.66
	Group	714.31	1	1.63	0.216	0.079
	Interactive effect	136.26	2	0.638	0.534	0.032
60°	Time	10205.72	2	23.77	<0.0001*	0.55
	Group	1558.69	1	1.49	0.237	0.073
	Interactive effect	226.36	2	0.527	0.594	0.027
90°	Time	8552.20	2	15.42	<0.0001*	0.44
	Group	190.73	1	0.168	0.686	0.009
	Interactive effect	1003.78	2	1.81	0.177	0.087

in the damaged fiber (Baumert et al., 2016) and, as a result, decreases the strength and range of motion (Baird et al., 2012). Also, based on pain adaptation theory, pain modulates muscle force and is a mechanism to protect the damaged tissue from further damage (Lund et al., 1991).

The present study was the first research in the field on the effect of the contraction velocity of the acute eccentric EIMD of the dominant knee extensor on running economy and metabolic responses. According to the results of this study, it appears that running economy and metabolic responses in trained young females are not influenced by contraction velocity of acute eccentric EIMD up to 48 hours after injurious activity. One of the reasons for the lack of effect of contraction velocity on the indirect indicator of muscle damage, running economy, and metabolic responses can be related to the type of muscle and the level of fitness of the subjects of this research, because the symptoms related to muscle damage caused by sports training depend on the training history and more severe responses have been reported in muscle groups that are less active than muscle groups that exercise regularly (Chen et al., 2011), and among skeletal muscles, the quadriceps muscle is involved in almost all physical activities such as running, walking, shooting, etc.

In general, results of research in the field of running economy following eccentric EIMD are contradictory and notable factors such as different muscle damage protocols and a wide variety of methods of evaluating running economy contributed to these differences. For example, the improvement observed in running economy, or in other words the oxygen consumption reduction in our study was inconsistent with the research that showed the lack of impact of eccentric EIMD on running economy (Satkunskiene et al., 2015; Vassilis et al., 2008) or the impairment of running

economy following EIMD (Burnett et al., 2010; Burt et al., 2013).

One of the reasons for the current study's inconsistent results, which showed a significant reduction in oxygen consumption at low intensities following the eccentric EIMD, was due to the muscles involved in the eccentric exercise. In the current study, the eccentric EIMD was only performed on the quadriceps muscle of the dominant leg, while in all other studies, both lower limbs were involved in the exercise, so it is possible that the increase in oxygen consumption and decrease in running economy in inconsistent research arising from a greater amount of damage and the longer duration of eccentric exercise. For example, the muscle injury protocol in inconsistent research was running on a treadmill with a negative slope and duration of 30 minutes, or performing 100 squats with an intensity of 80% of the body weight, and the entire lower limb was involved. While eccentric knee flexion with the isokinetic device used in the present research mainly leads to damage in the quadriceps muscle and has little or no effect on the biceps muscles and specifically the gastrocnemius and soleus muscles, which play a main role in running. There is also a possibility that the significant decrease in oxygen consumption after eccentric EIMD at 60 and 70% of the V_{O2max} was not due to the improvement of running economy and is a compensatory mechanism to reduce the re-injury of the muscle fibers. This issue can be attributed to the type of muscle fiber recruitment.

Because it has been shown that after eccentric training, slow-twitch motor units are responsible for producing a higher percentage of force compared to before training (Hight et al., 2017), and since submaximal muscle activity relies primarily on

type I fibers while maximal activity relies on type II fibers (Plotkin et al., 2021), it is possible that type I fibers may not be as damaged as type II fibers in this type of eccentric exercise have maintained their normal recruitment patterns and metabolic performance during submaximal running, used to assess running economy (Paschalis et al., 2005).

While in the higher intensity of running (80%) where type II fibers played a greater role, reducing oxygen consumption and improving running economy was not significant. It is also possible that the decrease in oxygen consumption following eccentric EIMD is caused by the disruption in the delivery and distribution of oxygen consumption in the capillaries of active muscles because it has been shown that serious microvascular disorders occur following this kind of exercise (Kano et al., 2005). In addition, mitochondrial rupture can lead to a decrease in oxygen consumption by muscle fibers and a decrease in hemoglobin kinetics following eccentric EIMD also leads to a disruption in the ability of the damaged muscle to extract oxygen from the bloodstream during exercise (Ahmadi et al., 2008).

Conclusions

In total, the findings of this research showed that four-fold difference in the contraction velocity (240 vs. 60°/s) of acute eccentric EIMD of the knee extensor of the dominant leg in trained females, when the muscle tension duration was equalized (300 contractions vs. 75 contractions) is not high enough to create a significant difference in the indices of muscle damage, running economy and metabolic responses. Also, the acute eccentric EIMD that is specifically performed on the quadriceps muscle that does not affect other muscles involved in running, does not negatively affect running economy after the injury and this effect is more evident in lower intensities of running.

What is already known on this subject?

All the studies conducted in the field of the effect of EIMD velocity have been focused on the flexor muscles of the elbow and upper limb and most of them have been conducted in male subjects with

Table 4. Repeated-measures analysis of variance of the maximal voluntary isometric torque of the dominant knee extensor at angles of 30, 60, and 90 degrees of the knee flexion.

Exercise intensity	Group Variable	High-velocity eccentric exercise (240°/s)		p Pretest vs. posttest	Low-velocity eccentric exercise (60°/s)		p-value Pretest vs. posttest	p-value Pretest of two groups	p-value Posttest of two groups
		Before exercise	48 hours after		Before exercise	48 hours after			
60% $v_{O_{2max}}$	Relative oxygen consumption (ml/kg.min)	30.2±4.87	27.90±3.60	0.005*	27.7±2.98	26.18±2.40	0.01*	0.24	0.210
	Heart rate (beats/min)	159.97±17.33	158.4±12.98	0.486	157.4±17.73	148.61±15.12	0.014*	0.74	0.129
	Minute ventilation (L/min)	51.75±9.32	47.5±6.26	0.017*	47.8±7.07	44.8±5.95	0.015*	0.29	0.312
	Respiratory exchange ratio	0.92±0.07	0.95±0.05	0.039*	0.91±0.05	0.93±0.04	0.284	0.63	0.23
70% $v_{O_{2max}}$	Relative oxygen consumption (ml/kg.min)	35.20±4.63	33.2±3.88	0.013*	33.2±3.82	31.63±3.61	0.005*	0.31	0.35
	Heart rate (beats/min)	174.21±11.57	173.6±10.01	0.727	170.8±16.8	165.76±17.26	0.002*	0.60	0.216
	Minute ventilation (L/min)	65.06±14.44	59.5±11.81	0.076	58.7±9.36	57.69±9.17	0.504	0.243	0.68
	Respiratory exchange ratio	0.93±0.08	0.98±0.05	0.014*	0.94±0.06	0.97±0.05	0.040*	0.92	0.77
80% $v_{O_{2max}}$	Relative oxygen consumption (ml/kg.min)	38.9±4.55	37.6±4.14	0.146	37.3±4.29	35.9±2.87	0.058	0.43	0.28
	Heart rate (beats/min)	185.30±8.57	184.04±8.52	0.602	180.6±15.2	177.87±15.17	0.134	0.409	0.26
	Minute ventilation (L/min)	76.99±17.86	73.8±14.31	0.227	69.9±11.88	70.85±11	0.701	0.299	0.592
	Respiratory exchange ratio	0.98±0.08	1.04±0.04	0.021*	0.98±0.06	1.02±0.05	0.002*	0.92	0.48

$v_{O_{2max}}$: the velocity to reach maximum oxygen consumption

an unequal duration of tension. In addition, the effect of EIMD on the running economy following different velocities of eccentric training is not well known, and due to the focus of research on one muscle group, the difference in the EIMD protocol, intensity, velocity and duration, the results are contradictory, and it is not possible to comment with certainty about the effect of contraction velocity.

What this study adds?

The present study was the first research that has investigated the effect of contraction velocity of the EIMD of quadriceps muscle with equal tension time on running economy and metabolic factors. In addition, the results showed that running economy and metabolic responses in trained young females are not influenced by contraction velocity of acute eccentric EIMD Up to 48 hours after injurious activity.

Organ Cross-Talk Tips:

- The cross-talk between damaged skeletal muscle and metabolic responses following eccentric exercise needs to be carefully identified (future perspective).
- Cross-talk between injured skeletal muscle and running economy following eccentric exercise needs further investigation (possible application).

Acknowledgements

This article is extracted from a doctoral dissertation. The authors would like to thank Dr Bahar Shaghayegh Fard for her help in data collection in the sports biomechanics laboratory.

Funding

The study was supported in part by a Kharazmi university.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Experimental protocols were approved (IR.SUMS.REC.1395.146) by the Ethics Committee of Shiraz University of Medical Sciences. Written informed consent was obtained from all participants.

Informed consent Written informed consent for publication was obtained from all participants.

Author contributions

Conceptualization: F.M., Z.H.F.; Methodology: .M., Z.H.F.; Software: F.M.; Validation: Z.H.F.; Formal analysis: .M., Z.H.F.; Investigation: .M., Z.H.F.; Resources: .M., Z.H.F.; Data curation:

.M., Z.H.F.; Writing - original draft: F.M.; Writing - review & editing: Z.H.F.; Visualization: .M., Z.H.F.; Supervision: F.M.; Project administration: Z.H.F.; Funding acquisition: F.M.

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