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Moderate intensity and volume downhill run does not impair knee joint stability at early and late phases of quadriceps/hamstrings contraction

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Abstract.
BACKGROUND AND OBJECTIVE: Muscle strength imbalance can be an important factor in hamstrings muscle strain. The main purpose of this study was to investigate the effects of downhill running on hamstrings/quadriceps torque (H/Q_{torque}) and the electromechanical delay (H/Q_{EMD}) ratios.
METHODS: Fifteen active male individuals performed two maximal voluntary isometric contractions of the knee extensors and knee flexors, from which the maximal muscle torque, EMD and H/Q_{torque} and H/Q_{EMD} ratios were extracted. Thereafter, the participants performed a 30-minute downhill run (−16%) at 70% VO_2max. Dependent variables were assessed immediately before, immediately following and 48 hours after the effort.
RESULTS: Maximal isometric torque decreased significantly immediately after the downhill run for both the extensors (pre: 271.8 ± 45.9 N·m; post: 235.5 ± 55.7 N·m) and flexors (pre: 112.2 ± 26.3 N·m; post: 97.7 ± 27.2 N·m). No significant difference was identified over time for the EMD of the vastus lateralis and biceps femoris muscles. The H/Q_{torque} and H/Q_{EMD} ratios were not influenced by the downhill run.
CONCLUSION: We have demonstrated that moderate intensity and volume downhill run does not impair knee joint stability at early (H/Q_{EMD}) and late phases (H/Q_{torque}) of quadriceps/hamstrings contraction.

Keywords: Strength, fatigue, muscle damage

1. Introduction

Muscular fatigue can be defined as a reduction of the strength-producing capacity of skeletal muscles induced by exercise [1]. Usually, fatigue symptoms are fully alleviated 24–48 hours after the exercise bout. However, in cases where the muscle performs high-volume eccentric contractions, some ultrastructural sarcomeric components (Z-line, sarcoplasmic reticulum, titin, etc.) are compromised, leading to a prolonged fatigue state known as exercise-induced muscle damage [2–4]. In this case, strength loss lasts longer due to the inflammatory response that occurs in order for the damaged structures to be properly rebuilt [2,5]. Many studies have used downhill running as a damage-inducing model because a large volume of eccentric contractions is required during this activ-

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ity, which may also lead to fatigue due to its long-term duration [6,7].

The ratio (H/Q_{torque}) between the maximal torque produced by the knee flexors (KF) and extensors (KE) has been widely studied and could be related to articular stability in the knee joint [8–10]. Epidemiological studies have demonstrated that muscle strength imbalance (i.e., impaired H/Q_{torque}) may play a central role in acute non-contact thigh muscle strain and anterior cruciate ligament injury [11]. Another factor that could lead to articular imbalance in the knee joint is the difference between the electromechanical delay (EMD) of the KE and KF during explosive actions. Hannah and colleagues [13] have suggested that this delay, which is defined by the time-course between the onset of the electrical stimulus and the onset of the force output, is longer for the KF than for the KE during explosive contractions. Notably sport-related injuries usually occur very early ($\sim$ 50 ms) during the contraction time-course [14]. Thus, prolonged hamstrings EMD might be responsible for knee joint instability and, consequently, some injuries during explosive actions [13].

It has been suggested that both fatigue and exercise-induced muscle damage lengthen EMD [15–18]. In fact, Conchola et al. [17] showed that fatigue induced by intermittent isometric contractions lengthened both the KF and KE EMD. However, this lengthening lasted longer for the KF than for the KE. Additionally, Howatson [18] found that muscle damage induced by maximal isokinetic eccentric contractions increased the EMD of the biceps brachii muscle. However, to the best of our knowledge, there have been no studies investigating the effects of downhill running-induced fatigue and muscle damage on EMD and markers of knee joint stability. Downhill running presents the stretch-shortening cycle and is performed at submaximal intensity. These characteristics can lead to a different pattern of fatigue and/or muscle damage. Baptista et al. [19] found that low-frequency fatigue, which is determined by ultrastructural damage, was similar between contraction types (concentric vs. eccentric) but was greater after maximal compared to submaximal eccentric fatiguing contractions. Thus, it would be interesting to investigate if the muscle damage induced by downhill running would compromise EMD and markers of knee joint stability.

Therefore, the aim of the present study was to investigate if the strength loss induced by a 30-minute downhill run would alter H/Q_{torque} and lengthen EMD immediately and 48 hours after the run, compromising knee joint stability.

2. Methods

2.1. Participants

Fifteen active male undergraduate students participated in the present study. The means of their age, height and body masses were 22.7 $\pm$ 4.4 years, 173.2 $\pm$ 7 cm and 72.8 $\pm$ 9.7 kg, respectively. None of them had experience with strength or endurance training during the 6 months that preceded the study as well as no medical history regarding articular and/or muscular injuries. All procedures adopted in the present study were conducted in accordance with the declaration of Helsinki for the use of humans as research subjects. The study was analyzed and approved by our institution's ethics committee.

2.2. Experimental design

The participants took part in a repeated measures design involving four laboratory visits over a 2-week period. All participants visited the laboratory on two different occasions (Visits 1 and 2) before the start of the experiment in order to become familiarized with the equipment and sign an informed consent form. During the visit 2, their maximal oxygen consumption (VO_2max) and the velocity at VO_2max (vVO_2max) were determined via an incremental ramp test on a treadmill (h/p/ comos pulsar – 3P, Nussdorf-Traunstein, Germany) with a 1% inclination gradient using a gas analysis system (Quark PFT Ergo, Cosmed, Italy). Thereafter, the participants had 7 days to rest before returning to the laboratory and performing a 30-minute downhill run at a speed equivalent to 70% of their vVO_2max at a -16% inclination gradient. Dependent variables were assessed immediately before, immediately after and 48 hours after the downhill run (Visits 3 and 4).

2.3. Experimental procedures

2.3.1. Downhill run

All participants performed a 30-min downhill run on the treadmill. The treadmill was set at a -16% gradient with a target intensity of 70% of vVO_2max, as determined from the incremental ramp test. Prior to beginning this run, each participant warmed up for 5 min on a treadmill set at 0% gradient using self-selected speeds.

2.3.2. Isometric peak torque

All criterion measures were analyzed from maximal voluntary isometric contractions (MVCs) of the KF and KE performed using a Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY). Participants were placed in a sitting position and securely strapped into the test chair. Extraneous movement of the upper body was limited by two crossover shoulder harnesses and an abdomen belt. The trunk/thigh angle was 85°. The axis of the dynamometer was lined up with the right knee flexion-extension axis, and the lever arm was attached to the shank by a strap. The volunteer was asked to relax their leg so that passive determination of the effects of gravity on the limb and lever arm could be measured. Two 5 second MVCs were performed for both the KF and KE at a fixed knee joint position of 70° (0 = full extension), with 180-s rest intervals between each MVC. These tests were performed in random order, using only the dominant (preferred kicking) limb. The volunteers were instructed to perform the MVC "as hard and fast as possible" and to hold until they were otherwise instructed. Examiners gave strong verbal encouragement during all MVCs. The MVC with the highest isometric peak torque for each muscle group was selected for analysis.

2.4. Data analyses

The torque data were collected through a data acquisition board (Miotool 200/400, Miotec, Porto Alegre, Brazil) that was fully synchronized with the dynamometer at a 1000 Hz frequency. All torque data were filtered (Butterworth filter, low pass, 4^{th} order, with a 15 Hz cut-off frequency) and analyzed using MatLab 6.5 (Mathworks, USA). The torque onset was defined as the time point where the KE and KF torque exceeded the baseline by 2.5% of the baseline-to-peak difference [20]. Isometric peak torque (IPT) was calculated as the greatest torque value obtained in the torque production curve. H/Q_{torque} ratio was calculated as the quotient of the KF IPT values and the KE IPT values.

2.5. Surface EMG recordings

The electromyographic signals (EMGs) of the vastus lateralis and biceps femoris muscles of the participants were assessed during all MVCs with the same data acquisition board (Miotool 200/400, Miotec, Porto Alegre, Brazil) used for torque analysis at a 1000 Hz frequency. Disposable adherent Ag/AgCl bipolar electrodes (MediTrace, São Paulo, Brazil), diameter: 2 cm, inter-electrode distance: 2 cm, were placed over the skin surface of the muscles, and one simple reference electrode was placed over the ulnar styloid process; both were connected to a preamplifier (100 times gain), following the SENIAM recommendations for electrode placement and EMG assessment [22], and connected to the data acquisition board, which promoted a 20 times gain. Prior to electrode application, the skin was shaved, abraded and cleansed with alcohol. The data analyses were performed using MatLab 6.5 while applying a high-pass filter (Butterworth, high pass, 2^{nd} order, with a 20 Hz cut-off frequency) and a low-pass filter (Butterworth, low pass, 4^{th} order, with a 500 Hz cut-off frequency). The average root mean square (RMS) value of the EMGs obtained at a 0.5 second interval during the MVC (i.e., 0.25 seconds before and 0.25 seconds after the IPT) was normalized by the peak RMS value obtained at the same time interval during the first experimental MVC. In this manner, all EMG values are expressed as percentages of the maximal RMS value (%RMS_{MAX}) of the baseline contraction.

2.6. Electromechanical delay

The electromechanical delay (EMD) of the vastus lateralis and biceps femoris muscles was calculated during the MVC, taking the time difference between the KE and KF EMG and torque onsets. For EMG onset, the signal was conditioned, and a visual manual detection was then performed [23]. First, the signal was conditioned with a band-pass 30–300 Hz (6^{th} order Butterworth) filter, which facilitates visual onset determination [24]. Then, the Teager-Kaiser energy operator (TKEO) was applied. The TKEO conditioning discrete function was defined as:

$$\varphi[x(n)] = x^2(n) - x(n+1)x(n-1) \qquad (1)$$

where x is the EMG signal and n is the sample number.

After TKEO was applied, the signal was rectified and low-pass filtered at 50 Hz (2^{nd} order, Butterworth, zero lag phase filter) to smoothly envelop the signal and reduce high-frequency noises [25]. Visual detection was performed with 1 ms resolution, and the onset was determined as the first muscle electrical activity above baseline [26,27]. The intraclass correlation coefficient for test-retest reliability for EMD of the vastus lateralis was previously calculated to be 0.74 [28].

2.7. Statistical analyses

The sample size ($n = 15$) was calculated considering a difference between means of 5% (effect size) and

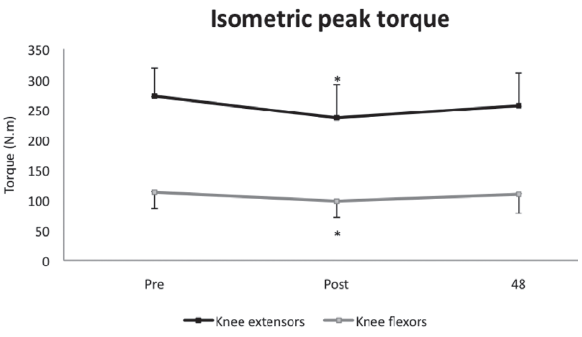

Fig. 1. Group mean ± SD values of isometric peak torque of knee extensor and knee flexor muscles before (pre), immediately after (post) and 48 h after a downhill run. $^*p < 0.05$ in relation to pre.

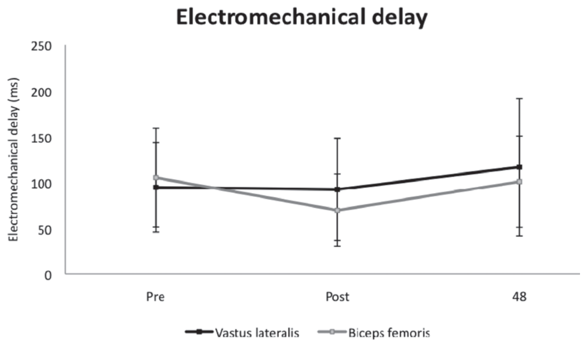

Fig. 2. Group mean ± SD values of electromechanical delay of knee extensor and knee flexor muscles before (pre), immediately after (post) and 48 h after a downhill run.

a 5% standard deviation, both obtained in pilot studies performed in the laboratory, adjusting the statistical power to 0.8 and the alpha error to 0.05. Data normality was tested using the Shapiro-Wilk test, and all normal data are expressed as the mean ± SD. Changes in dependent variables measured over time were tested via repeated ANOVA-F measures. Significance levels were set at $p \leqslant 0.05$, and all tests were conducted using SPSS 21.0.

3. Results

The mean VO_2max and vVO_2max values of the participants were 49.9 ± 5.8 mL·kg^{-1}·min^{-1} and 16 ± 2.2 km·h^{-1}, respectively. IPT decreased significantly immediately after the downhill run for both the KE (pre: 271.8 ± 45.9 N·m; post: 235.5 ± 55.7 N·m) and KF (pre: 112.2 ± 26.3 N·m; post: 97.7 ± 27.2 N·m) ($p < 0.05$). No significant difference was found between the baseline and 48 hours post-downhill run IPT values for both muscles ($p < 0.05$). IPT values are presented in Fig. 1.

No significant difference was identified over time for the EMD of the vastus lateralis (pre: 94.5 ± 48.6 ms; post: 92.3 ± 56 ms; 48: 116.6 ± 74.8 ms) and the biceps femoris muscle (pre: 105.2 ± 53.8 ms; post: 69.6 ± 39.5 ms; 48: 100.8 ± 49.7 ms), as shown in Fig. 2 ($p > 0.05$). The normalized vastus lateralis muscle EMG decreased significantly immediately after the downhill run, returning to baseline levels 48 hours later (pre: 64.6 ± 23.8% RMSmax; post: 55.1 ± 16% RMSmax; 48: 66.9 ± 27.2% RMSmax). Similar results were obtained for the normalized biceps femoris muscle EMG (pre: 63.9 ± 20.5% RMSmax; post: 49 ± 12% RMSmax; 48: 58.4 ± 18.5% RMSmax). The

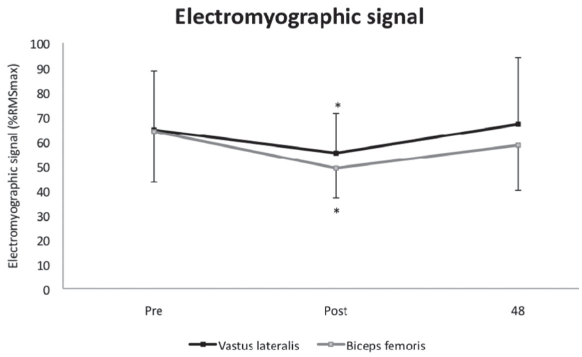

Fig. 3. Group mean ± SD values of normalized electromyographic signal of knee extensor and knee flexor muscles before (pre), immediately after (post) and 48 h after a downhill run. $^*p < 0.05$ in relation to pre.

normalized EMGs for both muscles are presented in Fig. 3.

Although IPT values changed acutely after the downhill run, H/Q_{torque} did not present any significant alteration in relation to baseline values at any of the measured time points (pre: 0.41 ± 0.09; post: 0.41 ± 0.08; 48: 0.42 ± 0.07) ($p > 0.05$). The H/Q_{EMD} was also not influenced by the downhill run at any of the assessed time points (pre: 1.42 ± 1.07; post: 1.49 ± 2.55; 48: 1.15 ± 0.93) ($p > 0.05$). Both H/Q_{torque} and H/Q_{EMD} ratio are graphically presented in Fig. 4.

4. Discussion

The main purpose of our study was to investigate whether downhill running would lead to significant fatigue, compromising the H/Q_{torque} and H/Q_{EMD} ratios, which could possibly impair knee joint stability. Similar to previous studies, we have demonstrated that

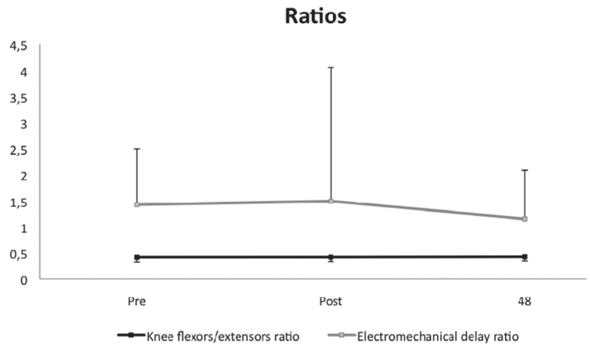

Fig. 4. Group mean ± SD values of knee flexors/knee extensors torque and electromechanical delay ratios before (pre), immediately after (post) and 48 h after a downhill run.

IPT (KE and KF) [6] and normalized EMG (vastus lateralis and biceps femoris) [29] were significantly impaired immediately after exercise-induced muscle damage. This study reveals, for the first time, that EMD, H/Q_{torque} and H/Q_{EMD} were not influenced by fatigue induced by downhill running. Thus, downhill running, performed at moderate intensity and volume (i.e., 30 min at 70% vVO_2max), might not necessarily impair knee joint stability during very early (H/Q_{EMD}) and late phases (H/Q_{torque}) from the onset of muscle contraction.

Downhill running is known to lead to fatigue, due to not only its metabolic requirement but also the exertional damage induced to the muscle tissue [6,7,30], which usually prolongs fatigue to 48–96 hours. In our study, however, strength loss (i.e., fatigue) was only identified immediately after the downhill running, returning to baseline levels 48 hours after the run. This fast recovery may be due to the slightly elevated fitness levels of the subjects who participated in the study [3, 31]. Additionally, if the dependent variables were assessed at a higher frequency (e.g., once a day), recovery could be better described. Nevertheless, fatigue was identified for both the KE and KF immediately after downhill running. Moreover, we observed that normalized vastus lateralis EMG was reduced immediately post-eccentric exercise, indicating that peripheral and/or central alterations occurred concurrently with IPT loss. Indeed, Racinais et al. [32] have verified that the torque decrement found immediately after a downhill walking exercise was associated with a decrease in voluntary activation (twitch interpolation). Moreover, Piitulainen et al. [33] found that the conduction velocity of action potentials was reduced during maximal voluntary contractions performed immediately after eccentric exercise. These data suggest that both central (neural drive) and peripheral (membrane excitability) alterations can explain the reduced muscle activation (normalized EMG) after exercise-induce muscle damage.

Most of the studies that investigated the fatiguing effects of downhill running assessed the strength of the KE because this type of activity requires numerous eccentric contractions of this muscle group, which leads to exercise-induced muscle damage [7]. Therefore, fatigue in the KE could possibly alter the H/Q_{torque}. However, we found that the KF force production was also impaired, resulting in unaltered H/Q_{torque}. The mechanisms behind the KE strength loss have been thoroughly discussed in the literature [34]. Among these mechanisms are ruptures in the z-line of the sarcomeres, disorganization of the sarcomeric apparatus as a whole, and sarcoplasmic reticulum disruption [3,33, 35], which are evident immediately after exercise [36]. These symptoms are triggered by a high degree of mechanical stress imposed on the muscle by high volumes of eccentric contractions as well as oxidative stress [37]. On the other hand, in our study, KF also presented strength loss, which could be justified by metabolic fatigue because this muscle group is responsible for part of the leg swing phase during running [38], which lasted 30 minutes. Therefore, we believe that, although caused by different mechanisms, fatigue was proportional in the KE and KF, causing the H/Q_{torque} to remain constant and not alter knee joint instability.

Hannah et al. [13] presented interesting data regarding the relationship between the EMD of KE and KF and knee joint stability at an early phase of contractions. The authors showed that the EMD of the latter was longer than that of the former, which could lead to knee joint imbalancing. Because most knee injuries occur at an early phase of contractions [14], it is important to ensure that the knee joint is properly stabilized at this time point. The mean EMD for the vastus lateralis (94 ms) and biceps femoris (105 ms) muscle across pre-exercise trial assessments in the present study was similar to the EMD observed for the knee extensors during isometric (106 ms) [39] and isokinetic actions (95 ms) [40]. There are conflicting reports about the influence of fatiguing exercise on EMD. Some studies have indicated that fatigue imposed by isometric [17], eccentric and concentric isokinetic contractions [34] leads to strength loss, which augments the EMD. However, as demonstrated in ours and other studies [39] neither of the assessed muscles had their EMD compromised by downhill running. H/Q_{EMD} was, consequently, not altered by fatigue. We believe that one of the reasons for this finding is the type of exercise performed. Previous studies have indicated that high-intensity contractions induced fatigue and alterations in EMD [15,16,18,34]. However, downhill running involvesthe stretch-shortening cycle and was based on moderate volumes of low-intensity eccentric contractions of the KE. Both characteristics can determine a lower disturbance in the neuromuscular apparatus [41], blunting the effects of fatigue on EMD.

Finally, there are a number of limitations that need to considered. First, no dynamic (concentric/concentric) or functional (eccentric/concentric) ratios were considered in the present study. Indeed, some studies have demonstrated that muscle fatigue differs according to the types of contraction utilized during its determination [42]. However, when multiple neuromuscular measures are performed, muscle fatigue can be underestimated, since significant recovery in skeletal muscle function occurs within the first 1–2 min after exercise [43]. Second, both fatigue and exercise-induced muscle damage are dependent on exercise duration/intensity. Thus, future studies should focus on investigating the effects of greater volumes of downhill and/or level runs on these ratios as well as on dynamic and functional ratios in order to better understand the effects of fatigue on knee joint stability.

5. Conclusion

Although acutely manifested, downhill running-induced fatigue does not impair H/Q_{torque} and H/Q_{EMD} ratios. Strength loss after this type of activity does not appear to be necessarily related to increased EMD and altered H/Q_{torque} and H/Q_{EMD} ratios of the KE and KF, which from a clinical point of view is a positive finding as knee joint stability is maintained. The two ratios represent distinct and important phases of muscle contraction (i.e., very early and late phases, respectively) that can affect knee joint injuries during sports and daily activities. Therefore, a fatigued status of the knee muscles after downhill run might not be of concern for coaches and practitioners.

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Competing interests

None declared.

References

[1] Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. Physiol Rev. 2001;81(4):1725-89.

[2] Clarkson PM, Hubal MJ. Exercise-induced muscle damage in humans. Am J Phys Med Rehabil. 2002 Nov;81(11 Suppl): S52-69.

[3] McHugh MP. Recent advances in the understanding of the repeated bout effect: the protective effect against muscle damage from a single bout of eccentric exercise. Scand J Med Sci Sports. 2003 Apr;13(2):88-97.

[4] Kanda K, Sugama K, Hayashida H, Sakuma J, Kawakami Y, Miura S, Yoshioka H, Mori Y, Suzuki K. Eccentric exercise-induced delayed-onset muscle soreness and changes in markers of muscle damage and inflammation. Exerc Immunol Rev. 2013;19:72-85.

[5] Paulsen G, Mikkelsen UR, Raastad T, Peake JM. Leucocytes, cytokines and satellite cells: what role do they play in muscle damage and regeneration following eccentric exercise? Exerc Immunol Rev. 2012;18:42-97.

[6] Chen TC, Nosaka K, Wu CC. Effects of a 30-min running performed daily after downhill running on recovery of muscle function and running economy. J Sci Med Sport. 2008 Jun; 11(3):271-9.

[7] Assumpção Cde O, Lima LC, Oliveira FB, Greco CC, Denadai BS. Exercise-induced muscle damage and running economy in humans. ScientificWorldJournal. 2013;2013: 189149. doi: 10.1155/2013/189149.

[8] Hewett TE, Myer GD, Zazulak BT. Hamstrings to quadriceps peak torque ratios diverge between sexes with increasing isokinetic angular velocity. J Sci Med Sport. 2008 Sep; 11(5):452-9.

[9] Zebis MK, Andersen LL, Ellingsgaard H, Aagaard P. Rapid hamstring/quadriceps force capacity in male vs. female elite soccer players. J Strength Cond Res. 2011 Jul;25(7):1989-93. doi: 10.1519/JSC.0b013e3181e501a6.

[10] Greco CC, da Silva WL, Camarda SR, Denadai BS. Fatigue and rapid hamstring/quadriceps force capacity in professional soccer players. Clin Physiol Funct Imaging. 2013 Jan; 33(1):18-23. doi:10.1111/j.1475-097X.2012.01160.x.

[11] Yeung SS, Suen AM, Yeung EW. A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor. Br J Sports Med. 2009 Aug;43(8):589-94. doi: 10.1136/bjsm.2008.056283.

[12] de Abreu Camarda SR, Denadai BS. Does muscle imbalance affect fatigue after soccer specific intermittent protocol? J Sci Med Sport. 2012 Jul;15(4):355-60. doi: 10.1016/ j.jsams.2011.11.257.

[13] Hannah R, Minshull C, Smith SL, Folland JP. Longer electromechanical delay impairs hamstrings explosive force versus quadriceps. Med Sci Sports Exerc. 2014 May;46(5):963-72. doi: 10.1249/MSS.0000000000000188.

[14] Krosshaug T, Nakamae A, Boden BP, Engebretsen L, Smith G, Slauterbeck JR, Hewett TE, Bahr R. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. Am J Sports Med. 2007;35(3):359-67.

[15] Cè E, Rampichini S, Agnello L, Limonta E, Veicsteinas A, Esposito F. Effects of temperature and fatigue on the electrome-

chanical delay components. Muscle Nerve. 2013 Apr;47(4): 566-76. doi: 10.1002/mus.23627.

[16] Minshull C, Eston R, Rees D, Gleeson N. Knee joint neuromuscular activation performance during muscle damage and superimposed fatigue. J Sports Sci. 2012;30(10):1015-24. doi: 10.1080/02640414.2012.682084.

[17] Conchola EC, Thompson BJ, Smith DB. Effects of neuromuscular fatigue on the electromechanical delay of the leg extensors and flexors in young and old men. Eur J Appl Physiol. 2013 Sep;113(9):2391-9. doi: 10.1007/s00421-013-2675-y.

[18] Howatson G. The impact of damaging exercise on electromechanical delay in biceps brachii. J Electromyogr Kinesiol. 2010 Jun;20(3):477-81. doi: 10.1016/j.jelekin.2009.08.002.

[19] Baptista RR, Scheeren EM, Macintosh BR, Vaz MA. Low-frequency fatigue at maximal and submaximal muscle contractions. Braz J Med Biol Res. 2009 Apr;42(4):380-5.

[20] Andersen LL, Andersen JL, Zebis MK, Aagaard P. Early and late rate of force development: differential adaptive responses to resistance training? Scand J Med Sci Sports. 2010 Feb;20(1):e162-9. doi: 10.1111/j.1600-0838.2009.00933.x.

[21] Maffiuletti, NA, Bizzini, M, Desbrosses, K, Babault, N, and Munzinger, U. Reliability of knee extension and flexion measurements using the Con-Trex isokinetic dynamometer. Clin Physiol Funct Imaging. 2007 Nov;27(6):346-53.

[22] Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J. Electromyogr Kinesiol. 2000;10(5): 361-74.

[23] Solnik S, Rider P, Steinweg K, DeVita P, Hortobágyi T. Teager-Kaiser energy operator signal conditioning improves EMG onset detection. Eur J Appl Physiol. 2010 Oct;110(3): 489-98. doi: 10.1007/s00421-010-1521-8.

[24] Latash ML, Aruin AS, Neyman I, Nicholas JJ. Anticipatory postural adjustments during self-inflicted and predictable perturbations in Parkinson's disease. J Neurol Neurosurg Psychiatry. 1995;58(3)326-34.

[25] Hodges PW, Bui BH. A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. Electroencephalogr Clin Neurophysiol. 1996;101(6):511-9.

[26] Brown JE, Frank JS. Influence of event anticipation on postural actions accompanying voluntary movement. Exp Brain Res. 1987;67(3):645-50.

[27] Horak FB, Esselman P, Anderson ME, Lynch MK. The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. J Neurol Neurosurg Psychiatry. 1984;47(9):1020-8.

[28] Jenkins ND, Palmer TB, Cramer JT. Comparing the reliability of voluntary and evoked muscle actions. Clin Physiol Funct Imaging. 2013 Dec 3. doi: 10.1111/cpf.12113. [Epub ahead of print]

[29] Vila-Chã C, Hassanlouei H, Farina D, Falla D. Eccentric exercise and delayed onset muscle soreness of the quadriceps induce adjustments in agonist-antagonist activity, which are dependent on the motor task. Exp Brain Res. 2012 Feb; 216(3):385-95. doi: 10.1007/s00221-011-2942-2.

[30] Kawanishi N, Kato K, Takahashi M, Mizokami T, Otsuka Y, Imaizumi A, Shiva D, Yano H, Suzuki K. Curcumin attenuates oxidative stress following downhill running-induced muscle damage. Biochem Biophys Res Commun. 2013 Nov 22;441(3):573-8. doi: 10.1016/j.bbrc.2013.10.119.

[31] Chen TC, Lin KY, Chen HL, Lin MJ, Nosaka K. Comparison in eccentric exercise-induced muscle damage among four limb muscles. Eur J Appl Physiol. 2011 Feb;111(2):211-23. doi: 10.1007/s00421-010-1648-7. Epub 2010 Sep 18.

[32] Racinais S, Bringard A, Puchaux K, Noakes TD, Perrey S. Modulation in voluntary neural drive in relation to muscle soreness. Eur J Appl Physiol. 2008 Mar;102(4):439-46.

[33] Piitulainen H, Bottas R, Komi P, Linnamo V, Avela J. Impaired action potential conduction at high force levels after eccentric exercise. J Electromyogr Kinesiol. 2010 Oct;20(5): 879-87. doi:10.1016/j.jelekin.2009.10.001.

[34] Pasquet B, Carpentier A, Duchateau J, Hainaut K. Muscle fatigue during concentric and eccentric contractions. Muscle Nerve. 2000 Nov;23(11):1727-35.

[35] Brentano MA, Martins Kruel LF. A review on strength exercise-induced muscle damage: applications, adaptation mechanisms and limitations. J Sports Med Phys Fitness. 2011 Mar; 51(1):1-10.

[36] Butterfield TA. Eccentric exercise in vivo: strain-induced muscle damage and adaptation in a stable system. Exerc Sport Sci Rev. 2010;38(2):51-60.

[37] Connolly DA, McHugh MP, Padilla-Zakour OI, Carlson L, Sayers SP. Efficacy of a tart cherry juice blend in preventing the symptoms of muscle damage. Br J Sports Med. 2006 Aug;40(8):679-83.

[38] Brown AM, Zifchock RA2, Hillstrom HJ3. The effects of limb dominance and fatigue on running biomechanics. Gait Posture. 2014 Mar;39(3):915-9. doi: 10.1016/j.gaitpost. 2013.12.007.

[39] Vos EJ, Harlaar J, van Ingen Schenau GJ. Electromechanical delay during knee extensor contractions. Med Sci Sports Exerc. 1991 Oct;23(10):1187-93.

[40] Nilsson J, Tesch P, Thorstensson A. Fatigue and EMG of repeated fast voluntary contractions in man. Acta Physiol Scand. 1977;101:194-8.

[41] Ryschon TW, Fowler MD, Wysong RE, Anthony A, Balaban RS. Efficiency of human skeletal muscle in vivo: comparison of isometric, concentric, and eccentric muscle action. J Appl Physiol. 1997 Sep;83(3):867-74.

[42] Oliveira Ade S, Caputo F, Gonçalves M, Denadai BS. Heavy-intensity aerobic exercise affects the isokinetic torque and functional but not conventional hamstrings:quadriceps ratios. J Electromyogr Kinesiol. 2009 Dec;19(6):1079-84. doi: 10.1016/j.jelekin.2008.10.005.

[43] Froyd C, Millet GY, Noakes TD. The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. J Physiol. 2013 Mar1;591(Pt 5):1339-46. doi: 10.1113/jphysiol.2012.245316.