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Research article

Functional and Neuromuscular Changes in the Hamstrings after Drop Jumps and Leg Curls

Nejc Sarabon [1,2]✉, Andrej Panjan [2], Jernej Rosker [1,2] and Borut Fonda [2,3]
[1] University of Primorska, Science and Research Centre, Institute for Kinesiology Research, Koper, Slovenia
[2] S2P, Science to Practice Ltd., Laboratory for Motor Control and Motor Behavior, Ljubljana, Slovenia
[3] University of Birmingham, School of Sport and Exercise Sciences, Birmingham, United Kingdom

Abstract
The purpose of this study was to use a holistic approach to investigate changes in jumping performance, kinaesthesia, static balance, isometric strength and fast stepping on spot during a 5-day recovery period, following an acute bout of damaging exercise consisted of drop jumps and leg curls, where specific emphasis was given on the hamstring muscles. Eleven young healthy subjects completed a series of highly intensive damaging exercises for their hamstring muscles. Prior to the exercise, and during the 5-day recovery period, the subjects were tested for biochemical markers (creatine kinase, aspartate aminotransferase, and lactate dehydrogenase), perceived pain sensation, physical performance (squat jump, counter movement jump, maximal frequency leg stamping, maximal isometric torque production and maximally explosive isometric torque production), kinaesthesia (active torque tracking) and static balance. We observed significant decreases in maximal isometric knee flexion torque production, the rate of torque production, and majority of the parameters for vertical jump performance. No alterations were found in kinaesthesia, static balance and fast stepping on spot. The highest drop in performance and increase in perceived pain sensation generally occurred 24 or 48 hours after the exercise. Damaging exercise substantially alters the neuromuscular functions of the hamstring muscles, which is specifically relevant for sports and rehabilitation experts, as the hamstrings are often stretched to significant lengths, in particular when the knee is extended and hip flexed. These findings are practically important for recovery after high-intensity trainings for hamstring muscles.

Key words: Isometric strength, stamping, balance, kinaesthesia, DOMS, EIMD

Introduction

Many kinds of resistance training are used as a method for the enhancing muscles` ability to generate power and helps athletes achieve maximum force in the shortest possible time (Michailidis et al., 2013). If a plyometric (i.e. stretch-shortening cycle (SSC)) muscle action is performed with high volume and intensity, it will often cause the delayed onset of muscle soreness (DOMS) (Hunter and Faulkner, 1997, Chatzinikolaou et al., 2010). This prolonged pain sensation is one of the most common recurrent consequence after damaging exercise (Clarkson and Hubal, 2002). Exercise-induced muscle damage (EIMD), which is one of the origin of DOMS, is characterized by the disruption of contractile and non-contractile proteins with the decomposition of sarcolemma (Lovering and De Deyne, 2004), increases in muscle proteins in the blood (Clarkson and Hubal, 2002), prolonged loss of muscle function (Clarkson and Tremblay, 1988), and swelling (Chleboun et al., 1998).

Plyometric exercise has been shown to elicit higher DOMS than concentric exercise but less than eccentric exercise (Brockett et al., 1997). The most important symptom of EIMD is probably a decreased ability to perform maximal voluntary contractions (MVC), encompassing both maximal force (Warren et al., 1999, Eston et al., 2003) and the maximal rate of force development (Strojnik and Komi, 1998, Vila-Chã et al., 2012). The MVC decrease can be up to 60% (Clarkson et al., 1992) and was shown to be smaller for locomotion muscles (e.g. knee extensors) when compared to the muscles in the upper extremities (e.g. elbow flexors) (Jamurtas et al., 2000).

Moreover, kinaesthesia (i.e. the joint position/movement/force sense) can also be modified as the result of muscle damage (Eston et al., 2003). Increased muscle stiffness after EIMD has been partially explained by changes in muscle spindle activity (Riemann and Lephart, 2002) and changed reflex sensitivity. These changes could have implications for performing skilled movements (Rosker and Sarabon, 2010). Significant impairments have been observed from 24 to 48 hours after damaging exercise, especially of joint position sense, the threshold to detect passive movement and force sense. Among the currently existing studies on the EIMD effects on proprioception, (Brockett et al., 1997; Saxton et al., 1995; Torres et al., 2010) only the study of Torres et al. (2010) examined the kinesthetic functions of the knee, while the rest focused on the elbow (Saxton et al., 1995, Brockett et al., 1997). The effects of EIMD on the kinesthetic functions of other sports-relevant muscle groups (e.g. hamstrings) remain unknown.

Furthermore, there is also a lack of information about the effects of EIMD on posture and balance, as well as on speed, agility and quickness. However, these aspects are important for training and competition performance, as well as for the prevention and rehabilitation of sports injuries in general. In this regard, there could hardly be a more relevant muscle group than the hamstrings. They are the soft-tissue structure with the highest prevalence of strains in sports that include sprinting, jumping, and kicking (Brooks et al., 2006; Croisier et al., 2002). Traumatic episodes commonly occur during the eccentric phase of a muscle contraction (Hoskins and Pollard,

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2005) which is accentuated in this bi-articular muscle group. Well-planned eccentric and SSC training are used in order to prevent hamstring strains and to improve their ability to produce power (Chimera et al., 2004). However, architectural characteristics and biomechanically challenging loading in several sports activities indicate that hamstrings could be more prevalent for EIMD than their antagonists. Furthermore, Chen et al. (2011) showed that hamstrings are more susceptible to muscle damage than the quadriceps. The majority of studies on EIMD in the lower extremities have focused on the quadriceps muscles, while those studying the effects on the hamstring muscles are scare (Brockett et al., 1997; Chen et al., 2011).

Therefore, the aim of this study is to use a comprehensive approach by investigating the changes in jumping performance, isometric strength, control of submaximal forces, static balance, isometric strength and fast alternating movements during a 5-day recovery period, following an acute series of damaging exercises with a specific emphasis on the hamstring muscles. We hypothesized that the results of all tests will be significantly changed with the most prominent changes in the tests that require more power and strength (vertical jumps and voluntary maximal torque production).

Methods

Subjects

Eleven, healthy young adults ([mean ± SD] age 26.9 ± 3.8 years, height 1.85 ± 0.08 m and weight 90.5 ± 3.8 kg) participated in the study. The subjects were familiar with damaging exercises, but did not perform this type of exercise for at least 3 months before the study. The subjects were instructed to maintain their normal eating patterns during the experiment and were not allowed to drink alcohol, take any medications or dietary supplements in the meantime. The details of the study were presented to them in an interview conducted before the start of the experiment. The study was approved by the National Medical Ethics Committee and all subjects signed a statement of informed consent in their enrolment.

Study protocol

Following a 15-minute warm up (8-minute easy running, 10 submaximal counter movement jumps and dynamic stretching) each subject performed a bout of damaging exercise, consisting of drop jumps and leg curls. They performed five sets of 10 drop jumps from a 0.6 m box with an emphasis on hip flexion-extension movement (range of motion ~100°). Emphasized flexion-extension movement has been achieved by oral instructions throughout the exercise. The subjects were instructed to execute active amortization and a maximally explosive push off. Drop jumps were followed by five sets of 10 repetitions of bi-lateral leg curls (75% of concentric 1RM) in a prone-lying position (hips at 20° flexion). The leg curls range of motion was ~90° with fast eccentric-concentric coupling at ~10° knee flexion angle. Finally, an additional set of ten repetitions of eccentric leg curls (130% of concentric 1RM; 3-second eccentric action with manually assisted lift) was performed in the same position. A series of drop jumps and leg curl exercises were interspersed with one-minute breaks. This protocol was used to apply two exercise tasks, one more sport specific and common for sport training (drop jumps) and second, specifically aimed to damage hamstring muscles and can be controlled (leg curls).

Blood samples from the cubital vein were collected prior to the damaging exercise bout and then 1, 24, 48, 72, 96 and 120 hours afterwards. After the blood samples were taken, the subjects underwent a series of tests in random order (pain sensation, squat jump, counter movement jump, single leg quite stance, high frequency leg stamping, maximal isometric torque, maximally explosive isometric torque, and a visio-motor torque tracking task).

Prior to the experiment the subjects came for three visits to familiarize themselves with the test procedure and to minimize bias (i.e. training effect) in certain tests. During these three visits they performed all the tests except giving blood samples, and were tested for the concentric 1RM leg curl exercise. No damaging exercise was performed during these visits.

Instrumentation

Venous blood samples (8 ml) were collected directly into serum separator collection tubes. CK, aspartate aminotransferase (AST), and lactate dehydrogenase (LDH) determined using an automated clinical chemistry analyzer (Olympus AU 680; Beckman Coulter, Nyon, Switzerland). Reference ranges for CK, AST and LDH were up to 168, 34, and 243 IU/L, respectively while level of analytical sensitivity was 2.94, 0.94, and 2.94 IU/L, respectively. Perceived pain sensation was assessed using a 10 cm visual analogue scale from 0 to 10, with 0 indicating no pain and 10 indicating severe pain. Precision of the scale was 1 millimeter. Pain was measured in resting conditions and during squat. Squat was performed in a smooth movement to a 90° knee and hip flexion in front of the examiner, who subjectively evaluated the amplitude of movement. Participants assessed soreness in their hamstring muscles.

Squat jumps, counter movement jumps, single leg stance and maximal frequency leg stampings were performed on a piezo-electric force plate (Kistler, model 9260AA6, Winterhur, Switzerland). The signals were acquired at 1,000 Hz and filtered with a low-pass Butterworth filter (20 Hz cut-off frequency, 2nd order) using commercially available software (Kistler MARS by S2P, Winterthur, Switzerland) (Sarabon, 2011).

Maximal torque production, explosive contractions and active torque tracking tests were performed on a static knee flexion measurement dynamometer (S2P Ltd., Ljubljana, Slovenia) using a strain-gauge sensor (HBM, Darmstadt, Germany) to measure knee flexion torque. The subjects were positioned prone on the dynamometer, with hips and knees flexed (45° and 60° respectively) All the tests were performed bilaterally. Custom-made software developed in LabVIEW 2010 (National Instruments, Austin, Texas, USA) was used for the acquisition and analysis of the signals. The force signal was acquired at 1,000 Hz and filtered with a low-pass Butterworth filter

(20 Hz cut-off frequency, 2nd order).

Criterion measures

Blood samples were tested for CK, AST, and LDH, as the most commonly used biochemical markers to confirm the onset of muscle damage (Clarkson and Hubal, 2002).

The following parameters were analyzed for the squat jump: jump height, start power (first 50 ms), maximal force, maximal power, work, push off duration, and the ratio between the force impulses of the second and the first half of the push off. The following parameters were analyzed for the counter movement jump: jump height, maximal force, maximal power, work, push off duration and duration of the counter movement. For the 20-second stamping test, the mean stamping frequency and mean force from the peaks were analyzed. The highest of the three squat jumps, and the highest of the three counter movement jumps, were used for further analysis. The foot stamping parameters were averaged for two trials.

Centre of Pressure (CoP) related parameters were analyzed to evaluate body sway during a quiet stance. The CoP mean velocity and area of 90% ellipse (36) were used as general balance indices, while direction specific (i.e. separately for anterior-posterior and medial-lateral direction) CoP parameters included mean velocity, mean amplitude and mean frequency of the power spectrum of the signal (Sarabon, 2010). All the parameters were calculated as an average value of the 60-second trial and averaged across three repetitions performed by each subject.

For voluntary maximal torque production, the peak average torque on a one-second time interval was calculated. Maximally explosive contractions of knee flexion were performed to evaluate the maximal rate of torque development and the average rate of torque development in the first 200 ms. The start of the torque rise was set at 3% of the peak value. Out of the three repetitions of maximal torque production and maximally explosive torque production, the repetition with the highest value was used for later analysis.

Furthermore, the subjects performed the task of active torque tracking using knee flexors contraction of submaximal intensity. The subject had to track a pseudo-random reference curve as precisely as possible. The reference curve was generated as a sine signal changing in frequency and amplitude (with the frequency ranging from of 0.1 to 1 Hz, and the amplitude ranging from 10 to 60 % of the maximal torque production). The range of the pseudo-random curve was adjusted for each subject separately, while frequency and the curve pattern were the same for all subjects. During the torque tracking task, online feedback was provided by a PC computer screen (17 inch), placed at a 1-meter distance from the subject. The visual feed-back was refreshed every 100 ms. Five thirty-second active torque tracking tasks with 60-second rest intervals were carried out. The same curve pattern, but with different starting points, was used to ensure the unpredictability of the reference curve in order to minimize the learning effect. The accuracy of the tracking was evaluated by normalized error (Kurillo et al., 2004) (Equation 1).

$$Normalized\ error = \left(\sqrt{\sum[(R - M)]^2 / [M_{amp}]^2 / N)]}\right) \cdot 100 \quad \text{Eq 1}$$

where R is the real-time torque trajectory, M is the reference torque trajectory, M_{amp} is the maximal amplitude of the reference trajectory and N is the number of total samples. Each subject performed five repetitions and the mean of the last three repetitions was utilized for further analysis.

Statistical analysis

For all of the measured parameters, the means and standard deviations were calculated across subjects. Shapiro-Wilk test was used to test for normality of the distribution and all parameters were found to be non-significant. A 1-way repeated measures analysis of variance and Bonferoni corrected *post hoc* t-tests were performed for each parameter to test for significant changes. The level of significance for all tests was set at $p \leq 0.05$. All statistical analyses were performed with IBM SPSS statistics 19.0 software (Armonk, NY, USA).

Results

The applied exercise protocol induced DOMS, as indicated by the increase in biochemical markers and perceived pain sensations after the exercise (Table 1). A statistically significant time effect was observed in CK ($F = 2.257$, $p = 0.05$) with the peak increase 24 hours post-exercise (1059 ± 2104 %). Sensations of pain during rest and during squats were significantly increased throughout the recovery period ($F = 14.678$; $p = 0$ .000 and $F = 26.142$; $p = 0.000$, respectively) where, in both conditions, the pain sensation peaked 48 hours post exercise.

Statistically significant time effects were observed for squat jump height, start power, maximal power, and work, while other parameters for squat jumps were not statistically significant (Table 2). Post-hoc comparisons revealed a statistically significant change compared to the baseline from 1 to 48 hours after the exercise for squat jump height ($p = 0.043 – 0.001$), 1 and 24 hours after the exercise for start power ($p = 0.031$ and 0.031, respectively), and 1 to 96 hours after the exercise for maximal power ($p = 0.000 – 0.038$).

Statistically significant time effects were observed for counter movement jump height, relative maximal

Table 1. Biochemical markers of exercise-induced muscle damage and perceived pain sensation. Values are mean (SD).

	Baseline	1h	24h	48h	72h	96h	120h	Time effect (p)
CK, IU/l	163 (106)	262 (167)	1264 (1706)	669 (607)*	1078 (1731)	1110 (1887)	763 (1201)	.050
AST, IU/l	24.5 (4.2)	29.4 (10.0)	43.7 (25.7)	39.9 (17.7)	45.0 (32.2)	47.1 (39.9)	42.5 (34.0)	.207
LDH, IU/l	175 (24)	184 (27)	187 (33)	195 (31)	210 (61)	195 (61)	187 (30)	.316
Pain rest, cm	.0 (.0)	.8 (.9)*	1.7 (1.2)*	1.9 (1.1)*	1.3 (0.7)*	0.2 (0.4)	0.1 (0.3)	.000
Pain squat, cm	.1 (.3)	2.3 (1.7)*	4.4 (1.6)*	4.7 (2.1)*	3.1 (1.7)*	0.8 (1.0)*	0.4 (0.5)*	.000

CK, creatine kinase; AST, aspartate aminotransferase; LDH, lactate dehydrogenase. * $p \leq 0.05$ *post hoc* t-test compared to Baseline.

Table 2. Squat jump and counter movement jump parameters. Values are mean (SD).

	Baseline	1h	24h	48h	72h	96h	120h	Time effect (p)
Squat jump								
Height, m	.265 (.021)	.254 * (.021)	.247 * (.024)	.247 * (.024)	.257 (.026)	.260 (.029)	.265 (.026)	.002
Start power, W/kg	.380 (.118)	.248 * (.055)	.251 * (.061)	.296 (.091)	.368 (.115)	.390 (.100)	.395 (.123)	.026
Max force, N/kg	22.3 (.9)	21.8 (1.1)	21.4 (1.7)	21.9 (1.0)	21.9 (1.5)	22.2 (1.6)	22 (1.2)	.279
Max power, W/kg	47.1 (3.2)	45.3 * (2.6)	44.6 * (2.8)	44.3 * (2.8)	45.9 (2.3)	45.7 * (2.7)	46.2 (2.3)	.000
Work, J	7.09 (.60)	6.82 (.67)	6.72 (.75)	6.67 (.62)	6.72 (.57)	6.91 (.76)	7.03 (.61)	.035
Push off, s	.403 (.044)	.404 (.041)	.404 (.033)	.401 (.026)	.388 (.021)	.411 (.063)	.414 (.024)	.474
Force impulse ratio, %	108 (34)	122 (30)	129 (40)	130 (27)	123 (27)	118 (24)	113 (20)	.115
Counter movement jump								
Height, m	.312 (.024)	.298 (.034)	.289 * (.033)	.300 (.032)	.314 (.036)	.312 (.046)	.314 (.038)	.005
Max force, N/kg	23.7 (1.5)	22.8 * (1.5)	21.3 * (1.2)	21.2 * (1.1)	21.6 * (1.3)	22.5 (1.6)	22.7 (1.8)	.000
Max power, W/kg	46.8 (2.4)	44.7 * (3.1)	44.2 * (3.0)	45.7 * (2.9)	46.2 (3.5)	46.5 (3.5)	46.3 (3.2)	.001
Work, J	8.52 (1.00)	8.27 (.68)	8.03 (.66)	8.25 (.70)	8.55 (.94)	8.50 (.91)	8.64 (0.79)	.035
Push-off, s	.317 (.025)	.336 * (.022)	.344 * (.027)	.342 * (.026)	.341 * (.029)	.339 * (.027)	.341 * (.024)	.001
Counter movement, s	.492 (.035)	.522 * (.043)	.548 * (.036)	.532 (.051)	.523 (.048)	.517 (.042)	.509 (.031)	.000

* $p \leq 0.05$ *post hoc* t-test compared to Baseline.

force, maximal power during counter movement jumps, work, and counter movement duration, while other parameters for counter movement jumps were not statistically significant (Table 2). Changes after the exercise, compared to the baseline, were statistically significant 24 hours after the exercise for counter movement jump height ($p = 0.030$), 1 to 72 hours after the exercise for relative maximal force during counter movement jumps ($p = 0.000 – 0.045$), 1 to 48 hours after the exercise for maximal power during counter movement jumps ($p = 0.002 – 0.032$), and 1 to 24 hours after the exercise for counter movement durations ($p = 0.030$ and 0.002, respectively).

Time effects were statistically significant for maximal torque and the maximal rate of torque development, while normalized errors during the visio-motor torque tracking test were not statistically significant (Table 3). Changes after the exercise compared to the baseline were statistically significant 1 to 96 hours after the exercise for maximal torque ($p = 0.000 – 0.027$) and throughout the whole 5-day recovery period for the rate of torque development ($p = 0.000 – 0.001$).

No statistically significant time effects were observed in any of the body sway and stamping parameters (Table 4). Moderate, but still not statistically significant changes, were only observed for the mean frequency of stamping ($F = 2.215$; $p = 0.054$).

Discussion

This study investigated the development of EIMD following damaging exercises for the hamstrings. The hamstring

Table 3. Maximal voluntary torque production and active torque tracking test parameters. Values are mean (SD).

	Baseline	1h	24h	48h	72h	96h	120h	Time effect (p)
Torque production								
Max torque, Nm	215 (41)	187 * (48)	180 * (43)	185 * (45)	198 * (45)	197 * (37)	203 (45)	.000
Max RTD, Nm/s	2716 (728)	2164 * (510)	1945 * (648)	2019 * (571)	2021 * (524)	2180 * (558)	2238 * (575)	.000
RTD 200 ms, Nm/s	718 (114)	645 * (132)	586 * (133)	604 * (145)	635 * (104)	661 * (121)	676 * (102)	.000
Max torque, Nm	215 (41)	187 * (48)	180 * (43)	185 * (45)	198 * (45)	197 * (37)	203 (45)	.000
Active Torque Tracking								
Norm. error, a.v.	6.15 (.34)	6.77 (.74)	6.60 (.90)	6.62 (.56)	6.49 (.69)	6.23 (.49)	6.23 (.45)	.170

RTD, rate of torque development. * $p \leq 0.05$ *post hoc* t-test compared to Baseline.

Table 4. Body sway and stamping parameters. Values are mean (SD).

	Baseline	1h	24h	48h	72h	96h	120h	Time effect (p)
Body sway								
V_{Σ} , mm/s	30.5 (5.1)	30.9 (6.4)	30.1 (5.4)	30.0 (4.9)	29.8 (4.8)	29.2 (5.1)	29.1 (4.7)	.765
$V_{a\text{-}p}$, , mm/s	17.6 (2.9)	17.5 (3.3)	16.9 (3.1)	16.9 (2.7)	16.8 (2.8)	16.3 (2.4)	16.4 (3.0)	.233
$V_{m\text{-}l}$, mm/s	21.5 (4.0)	22.1 (5.2)	21.6 (4.3)	21.5 (4.1)	21.3 (4.0)	21.0 (4.4)	20.9 (3.4)	.410
$A_{a\text{-}p}$, mm	10.2 (1.6)	10.3 (1.9)	10.2 (1.8)	10.1 (1.7)	10.2 (2.0)	9.9 (1.2)	9.6 (1.3)	.454
$A_{m\text{-}l}$, mm	13.1 (1.7)	13.6 (2.2)	13.1 (1.8)	13.0 (2.0)	13.3 (1.7)	13.0 (1.6)	13.2 (.9)	.411
$F_{a\text{-}p}$, Hz	.386 (.068)	.365 (.102)	.355 (.090)	.366 (.102)	.348 (.101)	.340 (.082)	.354 (.100)	.385
$F_{m\text{-}l}$, Hz	.482 (.101)	.517 (.120)	.518 (.107)	.500 (.137)	.534 (.113)	.520 (.145)	.518 (.105)	.274
90% elipse, mm^2	142 (48)	159 (65)	129 (36)	127 (36)	127 (37)	126 (25)	120 (25)	.054
Stamping								
Mean freq., Hz	9.3 (.9)	9.1 (.9)	8.7 (.7)	8.9 (.7)	9.1 (.9)	9.0 (.7)	9.1 (.8)	.054
Peak force, N/kg	13.7 (1.1)	13.5 (.9)	13.7 (0.9)	13.5 (1.0)	13.5(.8)	13.4 (.7)	13.4 (.8)	.232

V_{Σ}, velocity of the resultant COP movement; $V_{a\text{-}p}$, velocity in anterior-posterior directions; $V_{m\text{-}l}$ velocity in medial-lateral directions; $A_{m\text{-}l}$, amplitudes of the COP sway in medial-lateral directions; $A_{a\text{-}p}$, amplitudes of the COP sway in anterior-posterior directions; $F_{m\text{-}l}$ frequencies of oscillation in medial-lateral directions; $F_{a\text{-}p}$, frequencies of oscillation in anterior-posterior directions; 90% elipse, area of the elipse that contains 90% of the COP data. * $p \leq 0.05$ *post hoc* t-tests compared to Baseline.

muscle group is often exposed to high-intensity training during recreational and sporting activities that involve sprinting, jumping, and kicking (Brockett et al., 2001; Brooks et al., 2006; Croisier et al., 2002). The potential effects of damaging training could improve explosive strength (Chimera et al., 2004) or prevent hamstring strains, which are one of the most common soft-tissue injuries in agile sports (Croisier et al., 2002, Brooks et al., 2006). However, the majority of studies on EIMD in the lower extremities have been performed on the quadriceps muscles, while studies looking at the effects on the hamstrings are rare. Biochemical markers, pain sensation and performance parameters have all confirmed the onset of EIMD. To the authors' knowledge, this is the first study that has comprehensively evaluated the neuromuscular, biochemical and pain sensation response after such exercises with an emphasis on hamstrings.

Plyometric exercise has been shown to provoke more damage than concentric exercise, but less than eccentric exercise (Brockett et al., 1997). A number of studies have observed a prolonged reduction in maximal voluntary contractions after damaging exercise, but none of these studies focused on the hamstrings (Howatson and Milak, 2009; Miyama and Nosaka, 2004; (Nosaka et al., 2002; Vila-Chã et al., 2012). Miyama and Nosaka (2004) reported a ~40% reduction in the maximal torque of knee extensors 1 hour after the drop jumps. Maximal torque remained depressed for up to 48 hours after the exercise. We observed a less obvious reduction (8-14%) in maximal torque, although the recovery was longer (96 hours). Other studies focusing on eccentric exercises observed a decrease in maximal voluntary contraction between 15 and 50%, which in general remained decreased for up to 4 days after the exercises (Nosaka et al., 2002; Vila-Chã et al., 2012). To the authors` knowledge, only one study (Vila-Chã et al., 2012) reported a decreased rate of force development after eccentric exercises and none after damaging plyometric exercises. Their results showed a less substantial decrease (~20%) in the rate of force development compared to our study (15-40%). The rate of torque development in our study remained depressed throughout the entire recovery period. Overall, we can conclude that the hamstrings' explosive isometric contraction was affected to a greater extent than maximal isometric torque production. This seems to be related to the fact that hamstrings are designed for higher velocities and less force (Lieber and Fridén, 2000).

A number of studies have observed that EIMD causes a prolonged reduction in vertical jump height (Byrne and Eston, 2002; Horita et al., 1999; 2003). However, none of the studies had a deeper insight into the underlying changes in the vertical jump dynamics, which was one of the aims of this study. Rodacki et al. (2002) demonstrated that vertical jump inter-segment coordination can be affected as a result of acute fatigue in the knee flexor muscles. To our knowledge, no comparable study has been done within the EIMD context. The results of this study showed a more pronounced relative drop in the counter-movement jump height compared to the squat jump height 24 hours after the damaging exercise. However, the return back to the baseline values is slower for the height of the squat jump compared to the height of the counter movement jump. In contrast to that, maximal power during both vertical jumps showed a similar trend, recovering 72 hours after intensive damaging exercises. The maximal jump-related ground reaction force was substantially decreased only for the counter movement jump, which could be explained by the differences in body/joint positions at which maximal forces appear during each type of the jump. Namely, in the counter movement jump, the maximal force occurs during the initial phase of the push off (trunk leaned forward and hips flexed), while during the squat jump the maximal force occurs at the late phase of the push off (trunk and hips more extended) (Linthorne, 2001). The differences between both jumps were additionally present for the time-related parameters. From this data we could argue that the slower (sub) phases of the jumps could have had negative effects on the performance of power-oriented training under the EIMD conditions. The observed differences in the dynamics of the vertical jumps, taking place as a result of EIMD, seem to nicely reflect the biomechanical function of hamstring muscles in these movements. However, we have to bear in mind that damaging exercise used in this study partially involved also other muscle groups of the lower extremity. Therefore the drops in

jumping performance do not necessarily reflect only the hamstrings' damage.

Some previous studies have shown changes in the force sense following EIMD (35; 38), however, the results of this study are not in line with this. The type of the test which we used to evaluate the ability to voluntarily control the submaximal force may have accounted for the difference in the results. The constant availability of visual feedback is a major difference between the force tracking and force matching tests. Consequently, visual compensation for the impaired peripheral sensory information, following EIMD, may have occurred. Additionally, central mechanisms able to produce force without the presence of peripheral sensory information might have also compensated for the sensory loss. Moreover, the negative effects of EIMD have been shown to be more pronounced at higher force levels (Carson et al., 2002). As relatively low force levels were used in this study (60% and lower), relatively small errors in force sense might have been more easily compensated by the previously described mechanisms.

No effects of EIMD on the unilateral quiet stance were shown in this study. Only minor postural involvement of the hamstrings during the single legged upright stance might have been the reason for the absence of significant changes. Additionally, minor muscle activation and abundant degrees of freedom of the hip and thigh musculature, could probably have easily compensated for decreased hamstring function. Body sway might have been more affected by balance tasks demanding more significant postural involvement of the hamstrings. It is also worth noting that if different exercise protocol would be used, such as drop jumps performed from the angle joints could induce more muscle damage to ankle joint stabilization muscles and consequentially would have more effect on static balance. Dynamic balance tests, such as the limits of stability, functional reach test, or balancing on an unstable support surface, could be more appropriate for future studies.

Fast alternating leg movements are important for an athlete`s speed, agility and quickness. This study showed no effect of EIMD on the maximal frequency of on-place leg stamping. Even though the hamstrings' postural involvement during the stamping task was significant, the load demands were relatively low. Additionally, the complex movement task involves many muscle groups (e.g. lower-leg muscles) to compensate for the hamstrings` functional impairments.

The main limitations of he present study is that we cannot be sure how much muscle damage has been caused by the drop jumps, how much by the explosive leg curls and how much by the eccentric exercise. From the parameters observed we can see that the biggest drop was present for the tests mainly performed by hamstrings muscles (maximal torque, etc.) and less by tasks where more muscle groups was involved (squat jump, etc.). This could implicate that more damage to hamstrings muscles has been caused with leg curls, as both measurements of maximal torque and rate of torque development were performed s a knee flexion task.

To summarize, the exercises for hamstrings used in this study to provoke EIMD, resulted in the hypothesized deterioration of hamstring function. The results showed reduced performance in vertical jumping, maximal voluntary contractions and maximally explosive contractions, while changes were not present in the active visio-motor torque tracking test, static balance and fast frequency leg stamping. Athletes should strive to prevent the onset of EIMD, otherwise the efficiency of training could be affected. In the case of EIMD, a sufficient recovery (~120 hours) with regeneration techniques (Cheung et al., 2003) should be provided. Further studies should be focused on sport specific movements and also on comparison to their antagonists.

Conclusion

Changes in biochemical markers, pain sensation and muscle function after damaging exercises have been extensively studied. However, there is a lack of data for hamstrings, which are critical in many sports that involve sprinting, kicking and jumping. Hamstrings are bi-articular muscles and are often subjected to longer excursions, higher velocities and smaller forces. This could indicate a higher prevalence for EIMD compared to their antagonists. This study demonstrates that hamstring function is significantly reduced following sports with a specifically damaging exercise and that it fully recovers 120 hours after the exercise if the athlete is not adapted to this type of exercise. Coaches, strength and conditioning specialists, physiotherapists and other experts should therefore bear in mind that prevention of EIMD is crucial to maintaining a regular training regime, otherwise reduced ability to maximally activate muscles could not provoke enough training progress. Athletes should progressively increase the intensity of the exercise to, if possible, prevent EIMD and a long recovery.

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Key points

- Hamstring function is significantly reduced following specifically damaging exercise.
- It fully recovers 120 hours after the exercise.
- Prevention of exercise-induced muscle damage is cruicial for maintaining normal training regime.

AUTHORS BIOGRAPHY

Nejc ŠARABON
Employment
University of Primorska, Science and Research Centre, Institute for Kinesiology Research, Slovenia
Degree
PhD
Research interests
Motor control, musculo-skeletal injury prevention and rehabilitation.
E-mail: nejc.sarabon@zrs.upr.si

Andrej PANJAN
Employment
S2P, Science to Practice Ltd., Laboratory for Motor Control and Motor Behavior, Ljubljana, Slovenia
Degree

BSc
Research interests
Modeling of human movement with advanced methodological approaches.
E-mail: andrej.panjan@s2p.si

Jernej ROŠKER
Employment
University of Primorska, Science and Research Centre, Institute for Kinesiology Research, Koper, Slovenia. S2P, Science to Practice Ltd., Laboratory for Motor Control and Motor Behavior, Ljubljana, Slovenia
Degree
BSc
Research interests
Motor control and injury prevention.
E-mail: jernej.rosker@s2p.si

Borut FONDA
Employment
S2P, Science to Practice Ltd., Laboratory for Motor Control and Motor Behavior, Ljubljana, Slovenia. University of Birmingham, School of Sport and Exercise Sciences, Birmingham, United Kingdom
Degree
MSc
Research interests
Motor control, biomechanics and ergonomics during cycling and in the field of recovery.
E-mail: borut.fonda@s2p.si

✉ **Nejc Sarabon**
University of Primorska, Science and Research Centre, Institute for Kinesiology Research, Garibaldijeva 1, 6000 Koper, Slovenia