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Effect of Uni and Bilateral High-Intensity Sustained Isometric Contraction Exercise on Fatigue Related Changes in Quadriceps Femoris

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ABSTRACT

Background. It is well established that different types of exercise can provide central and peripheral fatigue. However, there are conflicting findings in the literature, and a consensus has not been reached regarding the different patterns of different ways of performing exercises when the muscle works at long and short lengths and unilaterally and bilaterally. The purpose of this study was to investigate the effect of muscle length and the high-intensity physical exercise when performing unilaterally and bilaterally on fatigue.

Methods. Thirteen young healthy physically active volunteering males participated in the study. Maximal voluntary and involuntary contraction was observed during the performance of sustained maximal (uni-)bilateral isometric contraction at long and short quadriceps muscle length. Capillary blood lactate concentration and perceived exertion was observed after high-intensity physical exercise.

Results. Maximal voluntary contraction (MVC)% decreased significantly and greatly in (uni-)bilateral exercise at long muscle length. CAR% at the appearance of fatigue was greater at long muscle length and did not depend on (uni-)bilateral contraction.

Conclusion. When both legs generate force (bilateral contraction), it is possible to observe a decrease in the rate of force development (RFD) but not in the MVC. Movement performed at long muscle length and (uni-)bilaterally has an effect on a greater motor cortex activation and a sense of movement effort and lactate concentration in capillary blood.

Keywords: high intensity interval exercise, sustained isometric contraction, central fatigue, peripheral fatigue, bilateral and unilateral contraction.

INTRODUCTION

High-intensity exercises are widely used in sports and health promotion (Bishop et al., 2019). Exercise performed at maximum intensity causes both peripheral and central fatigue (Brazaitis et al., 2012; Carroll, Taylor, & Gandevia, 2017; Skurvydas et al., 2016; Skurvydas & Zachovajevas, 1998) decreases energy stores in the muscles and accumulates metabolites (Cheng, Place, & Westerblad, 2018; McKenna & Hargreaves, 2008) which reduce Ca_2 + emissions from SR and myofibrillar Ca_2 + sensitivity (Allen, Jones, Tsay, Morgan, & Proske, 2018; Place et al., 2015). In addition, performing exercises in the isometric mode (and especially when the muscle is stretched over a long length) can also cause mechanical damage to the muscles (Skurvydas et al., 2016; Allen et al., 2018).

The decrease in muscle strength during exercise depends on many factors that are interrelated, as III/IV afferents signal the CNS and cardiovascular system and it responds to motor cortex activation and a sense of movement effort (Sidhu et al., 2018; Taylor, Todd, & Gandevia, 2006).

The higher the afferent flow of stimuli from the periphery, the greater the central fatigue, which protects the muscles from further exhaustion, because the peripheral muscle fatigue (the individual critical threshold of peripheral fatigue) is the prevailing factor limiting central motor drive (Amann & Dempsey, 2016; Blain et al., 2016; Hureau, Ducrocq, & Blain, 2016; de Morree, Klein, & Marcora, 2012).

Performing physical tasks with one leg (unilaterally) can make the muscles more fatigued than performing physical tasks with both legs (bilaterally) (Broxterman et al., 2018; Goodall, Howatson, & Thomas, 2018; Johnson, Sharpe, Williams, & Hannah, 2015; Rossman, Garten, Venturelli, Amann, & Richardson, 2014). Central fatigue is more pronounced in bilateral physicals exercise and peripheral fatigue – in bilateral exercise (Broxterman et al., 2018; Goodall et al., 2018; Rossman et al., 2014).

The bilateral strength deficit represents the reduction in performance during synchronous bilateral limb contractions compared to the sum of identical unilateral limb contractions (Jakobi & Chilibeck, 2001). There is no consensus on the bilateral strength deficit, the results and conclusions are controversial. Some researchers confirm its existence (Cornwell, Khodiguian, & Yoo, 2012; Girompaire, Morel, & Lapole, 2017; Matkowski, Martin, & Lepers, 2011; Van Dieen, Ogita, & de Haan, 2003), others do not (Jakobi & Cafarelli, 1998; Škarabot, Cronin, Strojnik, & Avela, 2016). Researchers argue that if there is a bilateral strength deficit, it is only because of the determination of methodological features (Buckthorpe, Pain, & Folland, 2013; Simoneau-Buessinger et al., 2015).

The purpose of this study was to investigate the effect of muscle length and the high-intensity unilateral and bilateral physical exercise on fatigue.

We hypothesized that because of a smaller amount of "sensory noise" during unilateral high-intensity physical task (6 series of MVC-60 s in each sustained isometric contraction), more fatigue will occur than during the bilateral task, and central fatigue will be greater when working bilaterally, and the stronger the fatigue, the higher the bilateral strength deficit, and especially the rate of force development (RFD).

METHODS

Participants in the experiment were 13 young healthy volunteering males (Table 1). All participants were non-smokers and rarely used caffeine. They were asked about the history of significant knee injury or surgery, pain in the knee joint or patella area during active or resisted knee movements, and knee instability feeling during functional activities within the past year. The participants were physically active and 2 to 3 times a week participated in various physical activities, such as running, cycling, handball, or tennis. They were asked to refrain from any exercise for one week prior to the experiment.

All participants gave their informed consent, which was approved by the Human Research Ethics Committee. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/ or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Table 1. **Physical characteristics of the participants**

n	13
Age (yr.)	22.4 ± 1.6
Height (cm)	180.7 ± 8.9
Weight (kg)	83.9 ± 10.2
BMI (kg/m^2)	24.1 ± 2.5
Body fat (%)	13.33 ± 2.8

Note. Values are expressed as means and SD.

Study design. To achieve success during the experiment day, reduce stress and fear of unexpected situations, ten to seven days before the experimental day, participants attended a familiarization session. During this session, participants were introduced to the experimental procedures, laboratory equipment and apparatus. They were trained to perform unilateral and bilateral maximal voluntary contractions in different positions of knee flexion.

All experimental sessions were planned to start at 8:30–11:30 a.m. The same experimental protocol was performed in four different modulations: 1) randomized unilateral testing at 60° of knee extension; 2) bilateral testing at 60° of knee extension; 3) randomized unilateral testing at 145° of knee extension; and 4) bilateral testing at 145° of knee extension; (full knee extension = 180°). Each participant performed all the trials with 7–10 days of break between them.

When participants arrived at the laboratory, they were seated in a special design chair for (uni-) bilateral muscle function testing (dynamometry). Knee angles of one or both legs (randomly) were set at 60° or 145°. Electrostimulation electrodes were attached to the right and left rectus femoris (RF) muscles (for bilateral testing) or randomly to the right or left sides of RF.

After 10 minutes of rest, the experimental protocols started in the laboratory environment. Firstly, electrostimulation and maximal voluntary contraction were measured by baseline measures. After baseline measurements, each participant completed a high-volume physical task consisting of 6 series of sustained maximal isometric (uni-)bilateral contraction (S1, S2, S3, S4, S5, S6), with 3 minutes of rest (Figure 1). In order to ensure maximal effort from the subjects, a vocal encouragement was provided by a researcher. Electrical muscle stimulation (ES) was applied at the 3rd, 30th and 57th seconds during sustained maximal voluntary contraction in order to measure central activation ratio (CAR).

Unilateral and bilateral force measurement. Participants were seated in special design chair with their back was supported on backrest, pelvis in a neutral position, hip angle at 110°. To keep upright and stabilized position, waist and chest were tied up with special belts. Participants were required to keep their arms crossed on their chest to avoid compensatory movements.

Participant's one or both legs were fixed with ankle belts 10 cm above malleolus. The axis of rotation of the lower limb attachments were aligned with the axis of rotation of participant's knee joints.

The force of rectus femoris of one or both legs were measured via LPU100 load cells (Transducer Techniques, Temecula, CA). The load cells were bolted to the bottom part of lower limb attachment and connected to the base of the chair by using rigid metal rod with a ball joint. Load cells were tested with static weights and calibrated prior to experiments. The initial signal levels were set to zero to correct for the weight of each limb. Force signals were amplified (gain = 40), digitized online by

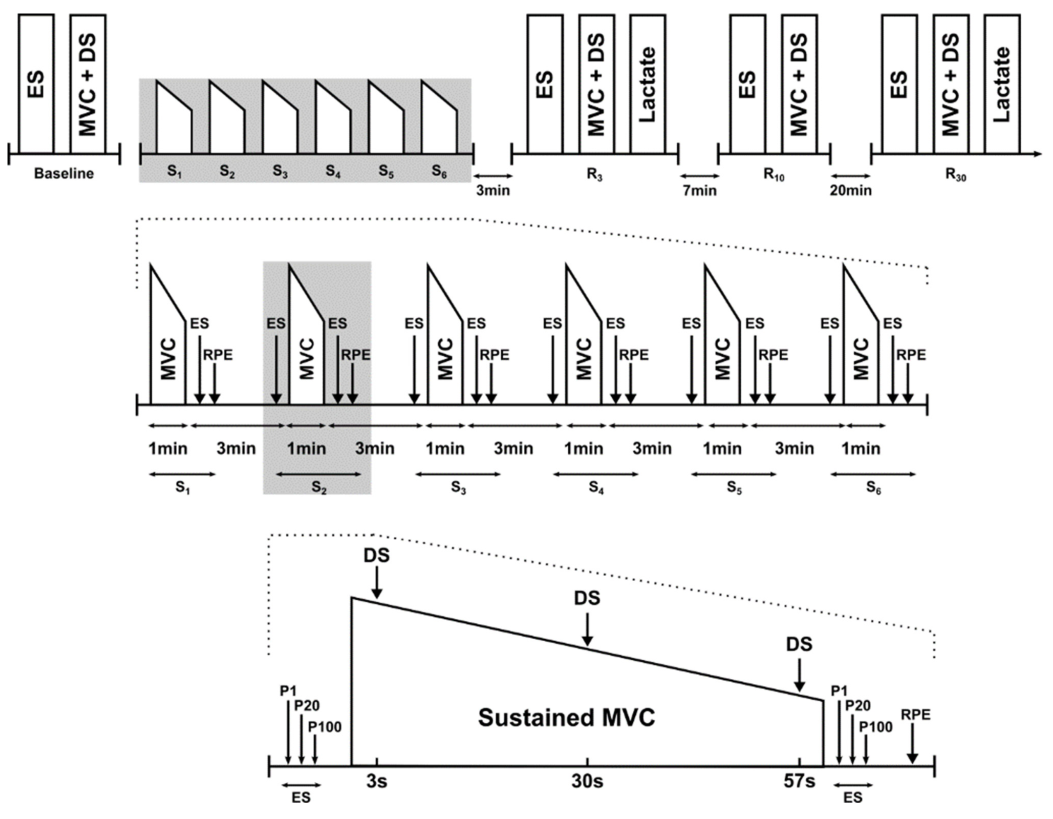

Figure 1. **Experimental protocol**

Notes. Representation of full experimental day protocol (part 1), representation of high-volume physical task series (part 2) and representation of single sustained maximal (uni-)bilateral isometric contraction (part 3). ES – electrical muscle stimulation, MVC – maximal voluntary contraction, DS – double twitch stimulus, R3 – rest time 3 min, R10 – rest time 10 min, R30 – rest time 30 min, S1, S2, S3, S4, S5, S6 – series number of sustained maximal (uni-)bilateral contraction, RPE – ratio of perceived exertion, P1 – 1 Hz stimulus, P20 – 20 Hz stimulus, P100 – 100 Hz stimulus.

BIOPAC MP150 data acquisition system (sampling rate – 1 kHz) and recorded simultaneously with Acqknowledge 4.1 software (BIOPAC Systems Inc., Goleta, CA).

Electrical stimulation. Direct muscle stimulation of quadriceps femoris was applied (uni-)bilaterally using carbonized rubber electrodes (FIAB, Italy) covered with a thin layer of ECG gel (Ceracarta, Italy). The anode (8 x 24 cm) was placed transversely across the width of the proximal portion of the quadriceps femoris and the cathode (8 x 12 cm) was placed on the distal portion of the muscle, above the patella. A high-voltage constant current stimulator (DS7, Digitimer Ltd, UK) was used to deliver electrical stimuli (monophasic square wave pulses; pulse width, 1 ms). Tetanic pulse (2 pulses; 1 ms duration, 10 ms interpulse interval) was used for CAR calculation (CAR was calculated using following equation: CAR = MVC/(MVC + P100 Hz) (Šatas, Jurgelaitienė, & Skurvydas, 2019).

Lactate concentration in capillary blood. The concentration of lactate in capillary blood was measured using a blood lactate meter (Lactate Pro2; Arkray, The Netherlands). Lactate was measured 3 min and 30 min after high-intensity interval isometric sustained physical exercise.

Perceived exertion. The modified Rate of Perceived Exertion scale (RPE) scale has a range from 0 to 10 (with 0 being no exertion and 10 being maximum effort). The perceived exertion was rated subjectively, asking to note and mark an effort level of 0 to 10 on a visual analogue scale. The question was given to each person immediately after each min of maximal voluntary sustained isometric contraction ("How much effort have you put into maintaining the performance of the task? Can you put more effort? If yes, please note that when you mark the line."). Then all exertion values were expressed as a percentage.

Statistical analysis. Data are reported as means ± *SD*. The data were tested for normal distribution using the Kolmogorov–Smirnov test, and they were found to be normally distributed. Statistical analysis involved general linear model analysis of variance (ANOVA) for repeated measures with FC and SC as a between-group factor, and time as within-group factor of two levels (before (baseline measurement) and after each of maximal voluntary sustained isometric contraction series or rest time post-physical exercise) on dependent variables (non-voluntary and voluntary maximal contraction (MVC) CAR, RFD, RFR of quadriceps femoris, capillary blood lactate concentration and perceived exertion). Observed power (OP) was calculated for all mechanical indicators based on an alpha level of .05, sample size (n ¼ 20), standard deviation and average level of variables. The level of significance was set at $p < .05$ and all statistical analyses were performed using IBM SPSS Statistics 22 (Armonk, NY).

RESULTS

Baseline values (pre-study measurement data) are presented in Table 2. Significant differences in MVC were observed between (uni-)bilateral SL-II and SL-I likewise LL-I and LL-II, also SL-II and LL-I baseline values. Involuntary contraction force at both (P20 and P100) stimuli were significantly greater when unilateral and bilateral tasks were performed at longer muscle length. No significant differences were observed in CAR, P1, P20/P100, P100 RFD and P100 RFR means.

Table 2. **Baseline values**

Indicators	SL-I	SL-II	LL-I	LL-II
MVC (N)	752.5 ± 159.7	585.9 ± 164.4 $^{\#}$	941.1 ± 201.4$^{\#}$	812.3 ± 201.8$^{+ ¢}$
CAR (%)	95.9 ± 1.6	94.3 ± 2.3	96.5 ± 1.6	95.4 ± 2.8
P1 (N)	67.1 ± 28.0	58.9 ± 28.8	74.5 ± 14.0	67.2 ± 31.8
P20 (N)	387.0 ± 102.0	363.0 ± 108.8	470.3 ± 101.4 $^{\#}$	457.3 ± 112.1 $^{+}$
P100 (N)	613.5 ± 112.2	562.3 ± 122.6	703.2 ± 200.8$^{\#}$	694.4 ± 146.2 $^{+}$
P20/P100 (%)	63.0 ± 11.6	64.3 ± 12.2	65.1 ± 6.4	62.8 ± 9.9
P100 RFD (N/s)	8256.0 ± 1376.0	7731.6 ± 1810.7	8224.2 ± 1707.7	7234.8 ± 2344.2
P100 RFR (N/s)	9182.2 ± 2017.5	9069.6 ± 2416.2	8383.0 ± 3266.0	8679.7 ± 3763.2

Note. SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; MVC – maximal voluntary contraction; CAR – central activation ratio; P1– 1 Hz stimuli (twitch); P20 – 20 HZ stimuli; P100 – 100 Hz stimuli; P20/P100 – ratio of 20Hz and 100Hz stimulus; P100 RFD – 100 Hz stimuli rate of force development; P100 RFR – 100 Hz stimuli rate force relaxation; + $p < .05$, vs SL-II; ¢ $p < .05$, vs LL-I; # $p < .05$, vs. SL-I.

Data on percentage variation of initial values of (uni-)bilateral force in different muscle length, MVC and CAR, are presented in Figure 2 (Figure 2 A shows results of maximal voluntary contraction when sustained maximal contraction performed at short muscle length (uni-)bilaterally, Figure 2 B – results of maximal voluntary contraction when sustained maximal contraction performed at long muscle length (uni-)bilaterally, Figure 2 C – results of central activation ratio when sustained maximal contraction performed at short muscle length (uni-)bilaterally; Figure 2 D – results of central activation ratio when sustained maximal contraction performed at long muscle length (uni-) bilaterally). MVC% when performing a physical task (uni-)bilaterally at long muscle length significantly decreased (F (3,36) = 11.59, p = .0001, η^2 = 0.491, OP = 0.99) after the first minute of sustained isometric contraction and do not recover 30 min past all 6 series. CAR% decreased more (F (3,36) = 8.39, p = .0001, η^2 = 0.411, OP = 0.98) and significantly when performed physical task on bilateral and at short muscle length. Compared meanings were found significant differences between unilateral and bilateral contraction in both short and long muscle length.

The data of involuntary (electrostimulation) contraction force at P1, P2 and P100 percentage variation of initial values are presented in Figure 3 (Figure 3 A shows results of P1 stimuli (twitch) when sustained maximal contraction performed at short muscle length (uni-)bilaterally, Figure 3 B – results of P1 stimuli (twitch) when sustained maximal contraction performed at long muscle length (uni-) bilaterally, Figure 3 C – results of P20 stimuli when sustained maximal contraction performed at short muscle length (uni-)bilaterally, Figure 3 D – results of P20 stimuli (twitch) when sustained maximal contraction performed at long muscle length (uni-) bilaterally, Figure 3 E – results of P100 stimuli when sustained maximal contraction performed at short muscle length (uni-)bilaterally, Figure 3 F – results of P100 stimuli when sustained maximal contraction performed at long muscle length (uni-) bilaterally, Figure 3 G – results of P20 and P100 ratio when sustained maximal contraction performed in short muscle length (uni-)bilaterally, Figure 3 H – results P20 and P100 ratio when sustained

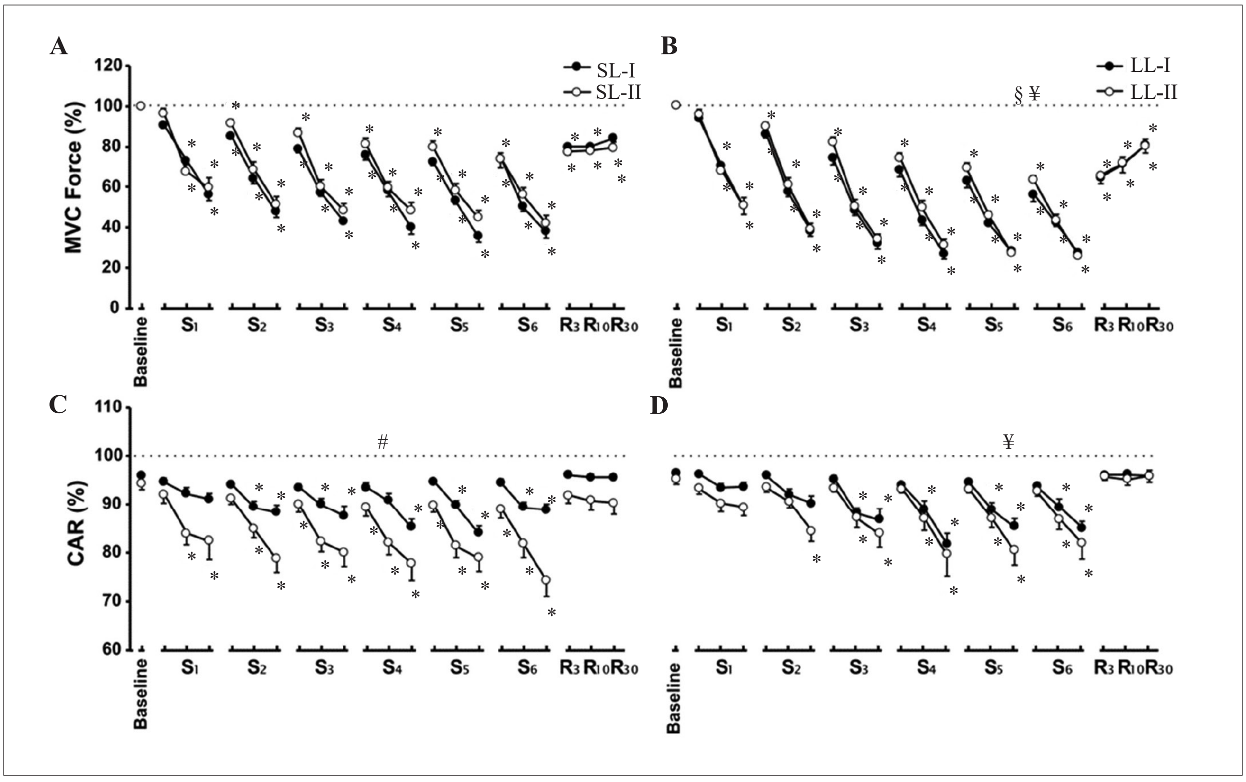

Figure 2. **Maximal voluntary contraction and central activation ration results after each series of sustained maximal (uni-)bilateral contraction**

Note. SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; *p < .05 with baseline; ¥ p < .05, SL-II vs LL-II; # p < .05, SL-I vs. SL-II, LL-I vs LL-II; §p < .05, SL-I vs LL-I.

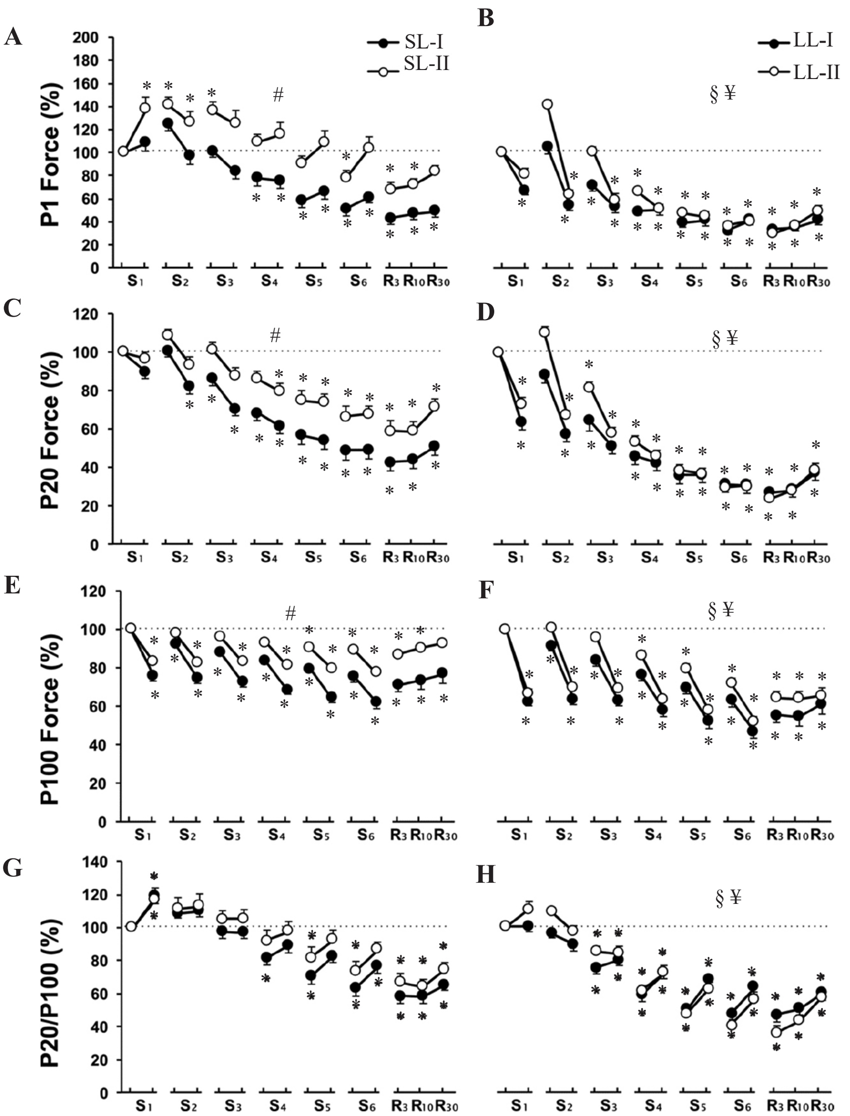

Figure 3. **Electrostimulation (non-voluntary contraction) results after each series of sustained maximal (uni-)bilateral contraction**

Note. SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; *$p < .05$ with baseline; ¥ $p < .05$, SL-II vs LL-II; # $p < .05$, SL-I vs. SL-II, LL-I vs LL-II; §$p < .05$, SL-I vs LL-I.

maximal contraction performed at short muscle length (uni-)bilaterally). Involuntary contraction force significantly decreased compared to baseline values of P1 (F (3,36) = 30.220, p = .0001, η^2 = 0.716, OP = 1.00), P20 (F (3,36) = 38.53, p = .0001, η^2 = 0.763, OP = 1.00), P100 (F (3,36) = 20.16, p = .0001, η^2 = 0.627, OP = 1.00). Comparing the values, we found significant differences between unilateral and bilateral involuntary contraction at both short and long muscle length of each of stimuli. P20 and P100 linear ratio significantly decreased (F (3,36) = 28.89, p = .0001, η^2 = 0.707, OP = 1.00) and did not recover 30 min after the task. Also, there were significant differences between values of (uni-)bilateral short and long muscle length performance.

Data on P100 RFD and P100 RFR percentage variation of initial values data are presented in Figure 4 (Figure 4 A shows results of P100 stimuli RFD when sustained maximal contraction performed at short muscle length (uni-)bilaterally; Figure 4 B – results of P100 stimuli RFD when sustained maximal contraction performed at long muscle length (uni-)bilaterally; Figure 4 C – results of P100 stimuli RFR when sustained maximal contraction performed at short muscle length (uni-)bilaterally; Figure 4 D – results of P100 stimuli RFR when sustained maximal contraction performed at long muscle length (uni-)bilaterally). P100 RFD values significantly decreased and did not recover compared to baseline values (F (3,36) = 12.88, p = .0001, η^2 = 0.518, OP = 1.00) likewise P100 RFR (F (3,36) = 3.76, p = .019, η^2 = 0.239, OP = 1.00). There were significant differences between values of (uni-) bilateral short and long muscle length performance.

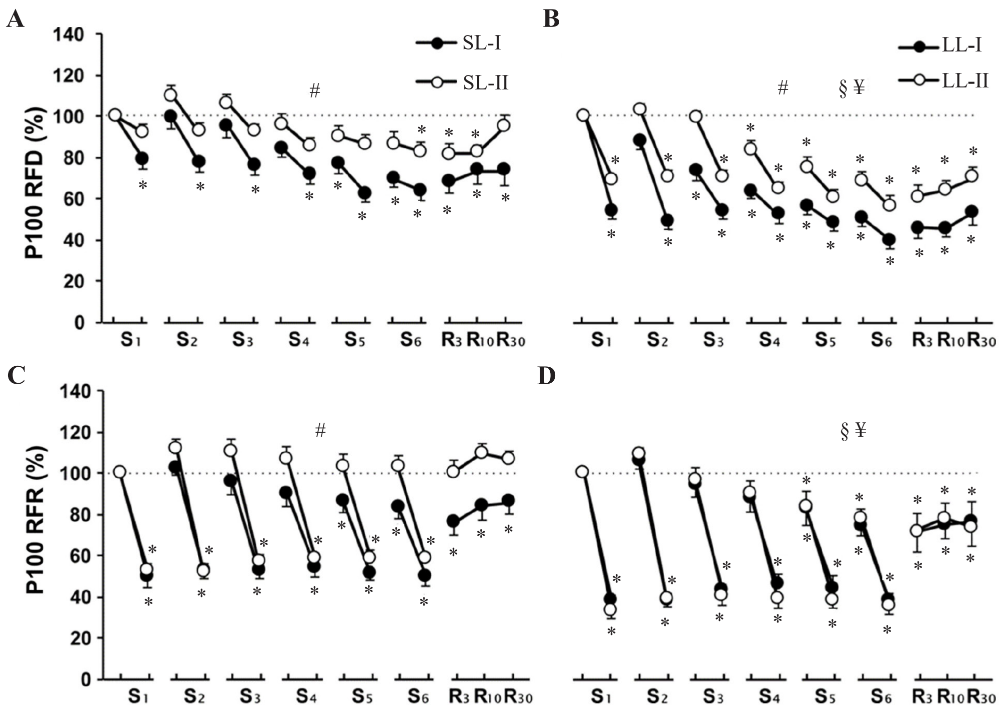

Figure 4. **Electrostimulation results after each series of sustained maximal (uni-)bilateral contraction**

Note. SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; *p < .05 with baseline; ¥ p < .05, SL-II vs LL-II; # p < .05, SL-I vs SL-II, LL-I vs LL-II; § p < .05, SL-I vs LL-I.

Figure 5 presents lactate concentration in capillary blood (mmol/L). Values 3 min and 30 min past (rest time) physical task significantly changed (F (3,36) = 5.362, p = .004, η^2 = 0.309, OP = 0.91). We observed significant difference between bilateral and unilateral short muscle length likewise unilateral and bilateral long muscle length values at 3 min of rest. Analogical results at 3min of rest were obtained comparing the values after 6 series of maximal sustained isometric voluntary contraction of bilateral short and bilateral long muscle length physical task.

The modified Rating of Perceived Exertion Scale results are given in Figure 6. No significant differences were found comparing physical tasks performed at short or long muscle lengths, where registered perceived exertion was significantly greater (F (5,60) = 17.320, p = .0001, η^2 = 0.591, OP = 1.00) when physical task was performed at long muscle length in (uni-)bilateral contraction.

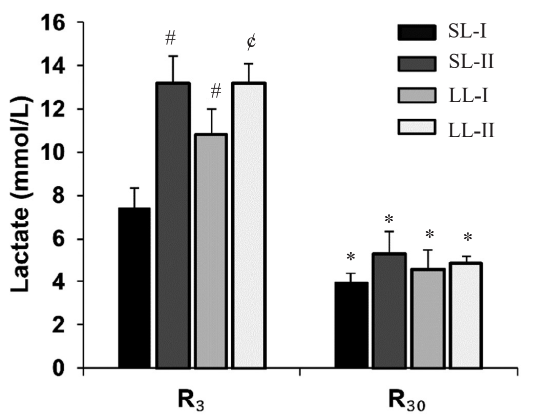

Figure 5. **Lactate concentration in capillary blood results 3 min and 30 min of rest time after high-intensity physical task of sustained maximal (uni-)bilateral contraction**

Note. SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; * p < .05 with R3 mean; # p < .05, SL-I vs SL-II, LL-I vs LL-II at R3 mean; ¢ p < .05, SL-II vs LL-II at R3 mean.

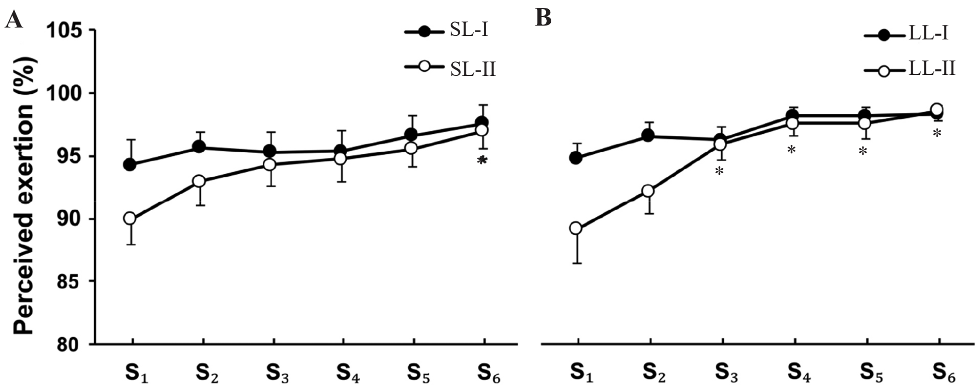

Figure 6. **The modified Rating of Perceived Exertion Scale results after each series of sustained maximal (uni-)bilateral contraction**

Note. SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; SL-I – short length unilateral; SL-II – short length bilateral; LL-I – long length unilateral; LL-II – short length bilateral; * $p < .05$ with 1 series (S1) of maximal voluntary sustained isometric contraction.

DISCUSSION

The purpose of this study was to investigate the effect of muscle length and the high-intensity physical tasks performing unilaterally and bilaterally on fatigue. The results of this study showed an increase in fatigue during the performance of sustained maximal voluntary unilateral and bilateral isometric contraction in physical tasks at both (short and long) muscle lengths and decreases in maximal voluntary contraction force as well as CAR.

As expected, bilateral high-intensity physical task develops a smaller involuntary contraction at both short and long muscle lengths than that performed unilaterally. We established that the more muscles work, the harder it is to cause the fatigue because the higher afference also causes more central fatigue (Goodall et al., 2018). Rossman et al. (2014) acknowledged the task-specificity of performance fatigability and proposed that a reduction in the exercising muscle mass permits the development of greater performance fatigability because of a reduction in the source of group III/IV afferent feedback, which can explain our present study results.

During high-intensity physical tasks with the muscle at long length resulted in greater fatigue and slower disappearance of it, as mechanical damage to the muscle could also occur, which is consistent with data in other studies (Allen et al., 2018).

As expected, bilateral muscle force declined during sustained maximal isometric contraction, but unilateral fatigability was higher compared to bilateral maximal sustained isometric contraction task of knee extension movement, and the finding is consistent with the results of Rossman at al. (2014).

It is suggested that: (1) during maximal bilateral contractions there exists a common drive from the central nervous system to the right and left muscles and the bilateral strength deficit is due to the decreased neural activations of the precentral motor cortex of both hemispheres; and (2) during bilateral contractions at submaximal level, a common drive also exists for simultaneous use of homologous muscles and the submaximal bilateral contraction is coordinated mainly under the control of the left hemisphere for right-handed people (Oda, 1997), but Kabacinski, Murawa, Mackala, and Dworak (2018) suggest no significant side-to-side strength deficits. In our present study, we did not find significant bilateral deficit in MVC.

In agreement with previous studies (Cornwell et al., 2012; Van Dieen et al., 2003; Maffiuletti et al., 2016; Ruiz-Cárdenas et al., 2018), it can be accepted that the bilateral deficit is higher in RFD than in MVC (Table 2). During the sustained maximal fatiguing contraction, RFDs decreased more than MVCs during fatigue and it can be explained by Morel at al. (2015) that the reduction of RFD is associated with an impairment of the ability of the central nervous system to maximally activate the muscle in the first milliseconds of the contraction (Mirkov et al., 2016).

CONCLUSIONS

Fatigue after 6 series of unilateral maximal sustained isometric contraction does not cause central fatigue especially when the movement is performed at short muscle length.

When both legs generate force (bilateral contraction), it is possible to observe a decrease in the RFD but not in the MVC. Movement performed at long muscle length and (uni-)bilaterally has an effect on a greater motor cortex activation and a sense of movement effort as well as lactate concentration in capillary blood.

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

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