Effects of high-intensity interval cycling performed after resistance training on muscle strength and hypertrophy

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Accepted for publication 19 July 2016

Aim of the study was to investigate whether high-intensity interval cycling performed immediately after resistance training would inhibit muscle strength increase and hypertrophy expected from resistance training per se. Twenty-two young men were assigned into either resistance training (RE; N = 11) or resistance training plus high-intensity interval cycling (REC; N = 11). Lower body muscle strength and rate of force development (RFD), quadriceps cross-sectional area (CSA) and vastus lateralis muscle architecture, muscle fiber type composition and capillarization, and estimated aerobic capacity were evaluated before and after 8 weeks of training (2 times per week). Muscle strength and quadriceps CSA were significantly and similarly increased after both interventions. Fiber CSA increased significantly and similarly after both RE (type I: 13.6 ± 3.7%, type IIA: 17.6 ± 4.4%, type IIX: 23.2 ± 5.7%, P < 0.05) and REC (type I: 10.0 ± 2.7%, type IIA: 14.8 ± 4.3% type IIX: 20.8 ± 6.0%, P < 0.05). In contrast, RFD decreased and fascicle angle increased (P < 0.05) only after REC. Capillary density and estimated aerobic capacity increased (P < 0.05) only after REC. These results suggest that high-intensity interval cycling performed after heavy-resistance exercise may not inhibit resistance exercise-induced muscle strength/hypertrophy after 2 months of training, while it prompts aerobic capacity and muscle capillarization. The addition of high-intensity cycling after heavy-resistance exercise may decrease RFD partly due to muscle architectural changes.

Human skeletal muscle has a remarkable ability to adapt to external stimuli such as exercise training. Different exercise modes induce specific muscle adaptations which may, however, oppose one another. For example, exercise training against high external resistances induces muscle hypertrophy resulting in enhanced muscle strength and power (American College of Sports Medicine, 2009; Cormie et al., 2011; Baar, 2014), while long-term endurance activities induce elevated muscle mitochondria, aerobic enzyme activities, and capillary density resulting in enhanced endurance capacity (Saltin & Gollnick, 1983). When low-intensity, long-duration aerobic exercise is combined with resistance exercise, muscle hypertrophy is impeded (for a meta-analysis see Wilson et al., 2012). This has often been attributed to the increased activation of AMPK after aerobic exercise which is believed to overpower the activity of mTORC and its downstream targets, a key pathway for the stimulation of the protein translation at the ribosomes after resistance exercise (Baar, 2014).

The impaired skeletal muscle hypertrophy with concurrent resistance and endurance training seems to be linked particularly with running and less with cycling (Wilson et al., 2012). In an earlier study, McCarthy et al. (2002) used continuous cycling at 70% of maximum heart rate reserve, three times per week either before or after resistance exercise and found similar increases in muscle mass and strength with either resistance exercise per se or concurrent resistance and aerobic-cycling training. Along this line, Hakkinen et al. (2003) used continuous endurance cycling two times per week, with various intensities on different training days and found similar increases in muscle mass and strength with either resistance exercise per se or concurrent resistance and aerobic-cycling training. In concert with the results of these chronic training studies, it was recently reported that muscle hypertrophy signaling after heavy-resistance exercise through the mTORC1-S6K1 axis was not inhibited by subsequent 30-min continuous cycling, instead, prior activation of mTORC signaling diminished subsequent
phosphorylation of AMPK (Apró et al., 2013). Similarly, mTORC signaling is not impaired when acute high-intensity interval cycling precedes resistance exercise (Apró et al., 2015), but in this case the increased expression of the ubiquitin ligases, MuRF1 and MAFbx, major regulators of protein breakdown, implies a interference effect on the hypertrophic molecular response. More recently, Pugh et al. (2015) reported that mTORC signaling is not impaired when high-intensity interval cycling (90–100% of VO\textsubscript{2max}) follows resistance exercise. This suggests that high-intensity aerobic cycling performed immediately after resistance exercise may not inhibit chronic muscle hypertrophy; however, this hypothesis has not been tested.

The addition of aerobic endurance exercise on resistance exercise results in impaired muscle power and rate of force development, regardless of the aerobic exercise mode (Wilson et al., 2012). This is a consistent finding despite the unimpaired muscle hypertrophy when cycling is used as the endurance training mode (Hakkinen et al., 2003). Changes in muscle architecture induced with concurrent training might be linked with this drop in the rate of force development since it has been postulated that endurance training might lead to decreases in fascicle length and increases in fascicle angle (Abe et al., 2000). Interestingly, a drop in gastrocnemius fascicle length was observed along with a shortage of muscle power increase after intense complex resistance and power training (Stasinakai et al., 2015), which suggests that muscle architectural changes might be linked with impeded muscle power development. However, little is known about muscle architectural adaptations with concurrent resistance and high-intensity interval cycling and whether these adaptations are linked with power performance changes.

The purpose of this study was to investigate whether high-intensity interval cycling performed immediately after resistance training would inhibit muscle hypertrophy and strength improvements induced by resistance training per se. Based upon previous studies utilizing low-intensity cycling as well as acute studies investigating molecular pathways it was hypothesized that high-intensity interval cycling performed immediately after resistance training would not hinder muscle strength and hypertrophy but would negatively affect the rate of force development.

Methods

Participants

Twenty-two male university students (age 21.8 ± 0.6 years, body height 177.4 ± 1.5 cm, body mass 74.2 ± 2.1 kg, estimated VO\textsubscript{2peak} on a cycle ergometer 38.2 ± 0.9 ml/kg/min) gave their written consent to participate in the study after being informed about the experimental procedures and the possible risks of the exercise training and testing as well as the possible hazards of the muscle biopsy procedure. They were not involved in systematic training (resistance or endurance) for at least 6 months before the initiation of the study, but they participated in recreational activities such as basketball, soccer, and jogging, 2–3 h per week, mostly during the weekends. In addition, throughout the study they continued their weekend recreational activities without participating in any other exercise training program. None of them had any musculo-skeletal or general health problems and none received any medication or nutritional supplements during the training period. Participants were assigned into two experimental groups according to their initial 1-RM leg press strength (procedure described below). One group of participants (RE, n = 11) performed resistance training only and the other group (REC, n = 11) performed the same resistance training but each session was followed by high-intensity interval cycling. One participant of the REC group did not finish the training program due to personal reasons unrelated to the study. Muscle biopsies were not obtained from one participant of the RE and one participant of the REC group. All participants were asked to keep their nutritional habits during the training period. None of them received dietary supplements during training. All procedures were approved by the local University Ethics Committee.

Procedures

Training

Training was performed two times per week for 8 weeks. Warm-up was the same for both training groups and included 5-min cycling at 50–75 W, lower body muscle stretching and 2 sets × 10 repetitions of three exercises for the trunk (abdominal crunches, lateral crunches, dorsal raises) aiming to strengthen the lumbar spine area for injury prevention. The inclined leg press (45° angle) and the half-squat (knee angle 90°) Smith machine were used for the strength training of the lower extremities. The RE group performed four sets of 6-RM for each exercise (Zaras et al., 2014; approximately 85% of 1-RM: 220 ± 14 kg and 127 ± 7 kg in leg press and in half-squat, respectively). In the first week, the training load was set at 80% of 6-RM (176 ± 11 kg and 102 ± 6 kg in leg press and half-squat, respectively; Izquierdo et al., 2006). Thereafter, the resistance training load was set at 6-RM and it was increased by 2.0–2.5% in every training session so as to maintain at 6-RM until the last week of training intervention. The rest between sets was 3 min and between the two exercises it was 5 min.

The REC group performed exactly the same resistance training but 10 min after the completion of the resistance exercises, the participants performed 10 sets of 60-s duration on a stationary bicycle with 100% of maximal aerobic power (Little et al., 2010; 100% W\textsubscript{max}: 183 ± 12 W) and 55–60 revolutions/min. The cycling work load was being increased (~2%) in every training session. The passive recovery between sets was 60 s. After termination of each training session all participants provided a rated scale of perceived exertion (RPE, 0: very-very light to 10: very-very heavy; McGuigan & Foster, 2004). The extra energy cost of performing high-intensity cycling in REC was less than 50 Kcal per day, for the whole training period. Therefore, the participants of the REC group did not receive any extra nutritional direction in order to compensate for this extra energy loss compared to RE.
Rate of force development

Participants were seated on a custom made steel leg press chair and placed both their feet on the force platform (WP800-1000 kg, 80 x 80 cm, sampling frequency 1 kHz; Applied Measurements Ltd Co., Aldermaston, UK) which was positioned perpendicular on a concrete laboratory wall. Knee angle was set at 120° and hip angle was set at 100° (Marcora & Miller, 1999). Participants were instructed to apply their maximum force as fast as possible for 3 s. Two maximum trials were performed with a 3-min interval. All participants were verbally encouraged to perform their best effort during the measurement. Variables calculated from the force-time curve included the maximum isometric peak force, the RFD and the impulse. Maximum isometric peak force was calculated as the highest force value obtained from the force-time curve. Rate of force development (RFD = \text{delta Force/ delta Time}) was calculated as the mean tangential slope of the force-time curve in specific time windows of 0–50, 0–100, 0–150, 0–200, and 0–250 ms, relative to the onset of contraction which was set at 2.5% of the difference between baseline and maximum force (Aagaard et al., 2002). Impulse was calculated as the area under the force-time curve and it represents the total force-time integral in a given time period \[\text{Impulse}_{0-k} = \sum F_{0-k} \times \Delta t_{0-k} \quad (k = 50, 100, 150, 200, 250 \text{ ms}).\] The best performance according to overall RFD (the average RFD calculated by means of RFD at 50, 100, 150, 200, and 250 ms) was used for further statistical analysis.

1-RM strength

Fifteen minutes after the RFD test, participants performed the 1-RM tests in the leg press and half-squat exercise according to standard guidelines (Buecle et al., 2000). Participants performed incremental efforts until they were unable to lift a heavier weight. Three minutes of rest was allowed between efforts and 30 min between the two exercise tests. In all cases, two of the researchers were present and vocally encouraged all participants, so that they performed their best.

Maximal aerobic capacity test

Two days after the strength tests, participants performed the maximal aerobic capacity test on a cycle ergometer (Monark ergomedic 834E, Vansbro, Sweden) during the morning hours. The aerobic capacity test was based on the adjusted YMCA Cycle Ergometer Protocol (American College of Sports Medicine, 2008). Specifically, participants started to cycle at 25 Watt with 50 rpm and every 3 min the resistance was increased by 25 Watt until the participants could no longer maintain the pedal speed. The increase in resistance in the second 3-min stage depended on the first-stage heart rate (HR, American College of Sports Medicine, 2008): if HR was under 80 beats per minute (b/min) at the end of the first stage, the resistance in the second stage was increased 100 Watt, if HR fluctuated between 80 and 90 b/min the resistance was increased 75 Watt, if HR fluctuated between 90 and 100 b/min the resistance was increased 50 Watt and if HR was over 100 b/min the resistance was increased 25 Watt. The HR was monitored and recorded throughout the aerobic test (Polar FT1 heart rate monitor, Polar Electro, Kempele, Finland).

Rate of perceived exertion (CR10 scale: 0: very-very light to 10: very-very heavy; Borg, 1998) was recorded separately for respiratory exertion (Central-Rating of Perceived Exertion/C-RPE) and for leg muscle and joint exertion (Local/Leg-Rating of Perceived Exertion/L-RPE; Ekbloom & Goldbarg, 1971) at the last minute of each 3-min stage (American College of Sports Medicine, 2008). When the test was completed, the work resistance was gradually decreased and the participants continued pedaling for 3–5 min order to prevent venous pooling.

Ultrasoundography

All ultrasound images both before and after the training intervention were obtained during the morning hours just before the muscle biopsy procedure. B-mode axial-plane ultrasound (Product model ZS, Shenzhen Mindray Bio-Medical Electronics Co., Ltd, Shenzhen, China) images were taken with a 10 MHz linear-array probe (38-mm width) with Extended-Field-Of-View (EFOV) mode. For the quadriceps CSA imaging, a line from the center of the patella to the medial aspect of the anterior superior iliac spine was marked and then an axial perpendicular line was drawn at 40% of this distance (proximal to the knee). Based on this marked line, the probe was moved transversely across the thigh taking a continuous single view which pictured the CSA of whole quadriceps with its’ four heads separately (Noorkoiv et al., 2010a). The CSA of whole quadriceps femoris (Quad) and each separate section (vastus lateralis-VL, rectus femoris-RF, vastus intermedius-VI, vastus medialis-VM) was analyzed using an appropriate image analysis software (Motic Images Plus, 2.0, Hong Kong).

For the measurement of vastus lateralis architecture, B-mode ultrasound images were taken at 50% of the distance from the central palpable point of the greater trochanter to the lateral condyle of the femur (Blazevich, 2006), using EFOV mode. A water-soluble gel was applied to the transducer to aid acoustic coupling and reduce the needed pressure from the probe. Against the muscle. The transducer was placed longitudinally on the femur, oriented in parallel to the muscle fascicles and perpendicular to the skin. However, due to individual differences, the transducer was sometimes aligned slightly diagonally to the longitudinal line of the muscle. Based on this orientation, a dashed line (~10 cm) was drawn from and back of 50% of the distance from the central palpable point of the greater trochanter to the lateral condyle of the femur, in order to identify and capture the largest, continuous fascicle visualization. To obtain the muscle image, a continuous single view was taken by moving the probe along the marked, dashed line. Also, the mediolateral angle of the probe was changed throughout the experiment, so that it remained perpendicular to the skin (Noorkoiv et al., 2010b). Images were analyzed for muscle thickness, fascicle angle, and fascicle length with image analysis software (Motic Images Plus, 2.0).

Muscle thickness was defined as the distance between the superficial and deep aponeurosis, fascicle angle as the angle of insertion of muscle fascicles onto the deep aponeurosis, and fascicle length as the fascicular path between the insertions of the fascicle onto the upper and deeper aponeurosis.

Muscle biopsies and histochemistry

Muscle samples were obtained using the standard Bergström needles, with suction, from the middle portion of vastus lateralis of the right leg under local anesthesia. The pre-training sample was obtained 20 cm from mid-patella and the post-training sample 5 cm proximally. The pre-training sample was obtained 3 days after performing the maximum aerobic test and 4 days before the initial training session, and the post-training sample was obtained 5 days after the last training session and 2 days after performing the final tests. All samples were aligned, placed in embedding compound and frozen in
isopentane, which was pre-cooled to its freezing point. All samples were kept in liquid nitrogen until the day of analysis. Serial cross-sections of 8-μm thickness were cut at −20°C and stained for myofibrillar ATPase after pre-incubation at pH 4.3, 4.6, and 10.3 (Brooke & Kaiser, 1970a,b). The samples obtained before and after the training period from each participant were incubated in the same session in the same jar. A mean of 687 ± 88 muscle fibers were classified as type I, IIA, and IIX from each sample. The cross-sectional area (CSA) of all the classified fibers was measured with an image analysis system (ImagePro, Media Cybernetics Inc, Silver Spring, MD, USA) at a known and calibrated magnification. The fiber type composition was expressed as the percent distribution of area and the percent distribution of the number of each fiber type. For the analysis of the capillary density, serial cross-sections of 10-μm thickness were cut at −20°C and stained with the amylase-periodic acid-Schiff reagent (PAS, Andersen, 1975). The capillary density was expressed as the number of capillaries per fiber (cap/fiber) and as the number of capillaries per mm² of muscle CSA (cap/mm²).

Statistical analysis

All data are represented as mean ± SD. Mixed analysis of variance (2 × 2 mixed ANOVA) was used to test the interaction between time (pre- and post-training) and intervention (RE and REC group). Post-hoc Bonferroni analysis was used to examine pairwise differences whenever a significant F-value was obtained. Independent samples t-test was used to detect differences in percent changes between RE and REC. Calculation of effect sizes (Cohen’s d for t-tests and η² for ANOVA) followed (Cohen, 1988; Keppel, 1991). Pearson’s r product-moment correlation coefficient was used to explore the relationship between different variables. Within subjects, variation and reliability were determined for all variables by calculating the confidence limits (95% CI) and Intraclass Correlation Coefficient (ICC) as described by Hopkins (2000). P < 0.05 was used as a two-tail level of significance. The ICC was calculated using a two-way mixed model to determine test–retest reliability for all dependent variables. All statistical analysis was performed using SPSS version 21.0 software (SPSS Inc., Chicago, IL, USA).

Results

Physical performance

Leg press and half-squat 1-RM were significantly increased in both groups [RE: 39.3 ± 4.9% (P < 0.001, d = 1.75), 30.5 ± 4.4% (P < 0.001, d = 1.463), respectively; REC: 32.3 ± 5.2% (P < 0.001; d = 1.345), 25.0 ± 3.0% (P < 0.001; d = 1.82), respectively (Table 1)]. The percent increase in 1-RM strength after training in both exercises was not significantly different between groups. Maximal isometric leg press force was increased significantly in both groups (RE: 21.1 ± 7.5%, P = 0.013, d = 0.916; REC: 9.5 ± 4.8%, P = 0.048, d = 0.301; Table 1) without any significant difference in the percent improvement between the two groups. The rate of force development at all time frames remained unchanged after RE but it was decreased (−30.0 ± 10.0%, P = 0.021, d = −0.949) at 50 ms after REC (Figs 1 and 2). Along this line, impulse at all time frames remained unchanged after RE but it was decreased significantly at 50, 100, and 150 ms after REC (50 ms: −22.6 ± 11.9%, P < 0.05, d = −0.756; 100 ms: −25.4 ± 9.6%, P < 0.05, d = −0.813; 150 ms: −20.8 ± 8.5%, P < 0.05, d = −0.671, Fig. 3). Both the percent change in RFD and Impulse at all time frames differed significantly between the two groups (P = 0.022–0.048, d = 1.07–0.913). RFD at 50 and 100 ms, as well as Impulse at 100, 150, 200, and 250 ms was higher in REC than in RE at baseline (P < 0.05). Maximal aerobic power was significantly increased after REC (16.5 ± 3.2%, P < 0.001, d = 0.612) but remained unchanged after RE (Table 1). A significant interaction between time and intervention for the maximal aerobic power was observed (P = 0.027, η² = 0.232). Also, the HR at 100 and 125 Watts workloads during the cycle ergometer test were decreased in REC (P = 0.043, d = −0.256 and P = 0.019, d = −0.252, respectively) but they were not changed in RE (Fig. 4). No difference in RPE after the training sessions was observed between RE and REC (RE: 8.50 ± 0.15; REC: 8.59 ± 0.12; P = 0.614, d = 0.222). Body mass was not significantly altered in either group (RE: before: 73.9 ± 2.9 kg, after: 74.8 ± 2.9 kg; REC: before: 72.4 ± 2.7 kg, after: 73.3 ± 2.8 kg, P > 0.05).

Quadriceps muscle CSA and architectural characteristics (ultrasongraphy)

The CSA of whole quadriceps muscle as well as for each of the quadriceps heads was significantly increased in both groups (P = 0.000–0.016, d = 2.113–0.864), except for the CSA of rectus

Table 1. Physical performance before and after the training period

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resistance training (n = 11)</th>
<th>Resistance+aerobic training (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>1-RM leg press (kg)</td>
<td>258.6 ± 16.2</td>
<td>355.9 ± 17.2&lt;sup&gt;±&lt;/sup&gt;</td>
</tr>
<tr>
<td>1-RM half-squat (kg)</td>
<td>149.5 ± 8.7</td>
<td>191.8 ± 7.7&lt;sup&gt;±&lt;/sup&gt;</td>
</tr>
<tr>
<td>Maximal isometric force (N)</td>
<td>3169.1 ± 193.5</td>
<td>3758.6 ± 194.4*</td>
</tr>
<tr>
<td>Maximal aerobic power (Watt)</td>
<td>179.6 ± 11.6</td>
<td>188.6 ± 10.9</td>
</tr>
</tbody>
</table>

1-RM = one repetition maximum strength.
*P < 0.05, <sup>±</sup>P < 0.001 difference between before and after training.
femoris and vastus medialis after RE, which was enlarged but not significantly (Table 2). The percent change in quadriceps CSA, vastus intermedius, and vastus medialis CSA was not different between the two groups. Interestingly, the percent change in vastus lateralis CSA was significantly greater in RE compared to REC ($P = 0.017$, $d = 1.135$) but the percent change in CSA of rectus femoris was significantly greater after REC ($P = 0.049$, $d = 0.929$). A significant interaction was found between time and intervention for the change in vastus lateralis CSA ($P = 0.046$, $\eta^2 = 0.194$).

Vastus lateralis thickness was significantly increased in both groups (RE: $9.1 \pm 2.4\%$, $P = 0.003$, $d = 0.525$; REC: $11.7 \pm 2.6\%$, $P = 0.003$, $d = 0.899$) without any statistically significant difference in the percent increase between groups (Table 2). Fascicle angle was increased significantly only in REC ($13.5 \pm 5.1\%$, $P = 0.027$, $d = 0.737$, Table 2). Fascicle length did not change significantly after either intervention (Table 2).

**Muscle fiber morphology**

The CSA of type I, IIA, and IIX muscle fibers increased significantly after both RE (type I: $13.6 \pm 3.7\%$, $P = 0.005$, $d = 1.411$; type IIA $17.6 \pm 4.4\%$, $P = 0.001$, $d = 0.986$; type IIX: $23.2 \pm 5.7\%$, $P = 0.008$, $d = 0.72$) and REC (type I: $10.0 \pm 2.7\%$, $P = 0.016$, $d = 0.373$; type IIA: $14.8 \pm 4.3\%$, $P = 0.008$, $d = 0.434$; type IIX: $20.8 \pm 6.0\%$, $P = 0.003$, $d = 0.591$; Fig. 5), with no significant difference between groups. The percent change in type IIA fiber CSA was significantly correlated with the percent change in maximal isometric force ($r = 0.593$, $P = 0.007$). The percentage of type IIX muscle fibers was decreased significantly after both RE (Before: $24.2 \pm 4.8\%$ vs After: $16.0 \pm 4.0\%$, $P = 0.028$, $d = 0.759$).
Fig. 3. Impulse (Ns) at 50, 100, 150, 200, 250 ms before and after 8 weeks of resistance training only (RE, a), and resistance plus aerobic training (REC, b). *P < 0.05 significant difference before and after training.

Fig. 4. Heart Rate at four submaximal workloads before and after 8 weeks of resistance training only (RE, a), and resistance plus aerobic training (REC, b). *P < 0.05, difference between before and after 8-week training period.

Table 2. Cross-sectional area of the right quadriceps and its' four heads, and architectural characteristics of vastus lateralis before and after 8 weeks of resistance training per se and resistance plus high-intensity aerobic cycling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resistance training (n = 11)</th>
<th>Resistance + aerobic training (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>CSA Quad (cm²)</td>
<td>75.8 ± 3.5</td>
<td>95.2 ± 5.0†</td>
</tr>
<tr>
<td>CSA VL (cm²)</td>
<td>20.0 ± 1.0</td>
<td>29.2 ± 1.9‡</td>
</tr>
<tr>
<td>CSA RF (cm²)</td>
<td>13.3 ± 0.8</td>
<td>14.1 ± 0.9</td>
</tr>
<tr>
<td>CSA VI (cm²)</td>
<td>28.2 ± 1.8</td>
<td>36.5 ± 2.2†</td>
</tr>
<tr>
<td>CSA VM (cm²)</td>
<td>14.4 ± 0.9</td>
<td>15.5 ± 0.6</td>
</tr>
<tr>
<td>VL thickness (cm)</td>
<td>2.5 ± 0.1</td>
<td>2.7 ± 0.1**</td>
</tr>
<tr>
<td>VL fascicle angle (°)</td>
<td>21.6 ± 1.1</td>
<td>22.2 ± 0.9</td>
</tr>
<tr>
<td>VL fascicle length (cm)</td>
<td>6.9 ± 0.4</td>
<td>7.2 ± 0.3</td>
</tr>
</tbody>
</table>

*P < 0.05, **P < 0.01, †P < 0.001 difference between before and after training.

†P < 0.05 difference in percentage changes between two groups (RE<REC).

‡P < 0.05 difference in percentage changes between two groups (REC<RE).

VL = vastus lateralis; RF = rectus femoris; VI = vastus intermedius; VM = vastus medialis; CSA = cross-sectional area; Quad = whole quadriceps.
The number of capillaries per muscle fiber was increased only after REC (5.8 ± 2.1%, $P = 0.031$, $d = 0.287$) while the capillary density per mm$^2$ of muscle tissue was unchanged after both RE and REC (Fig. 7). When all participants were considered together, the percent change in vastus lateralis CSA was negatively but significantly correlated with the percent change in capillaries per fiber ($r = -0.521$, $P = 0.022$).

**Discussion**

The main finding of this study was that high-intensity interval cycling performed immediately after lower body resistance training did not inhibit muscle hypertrophy induced by chronic resistance training, in moderately trained individuals. Both the muscle...
fiber CSA of all fiber types and the quadriceps muscle CSA determined by ultrasonography were increased similarly with or without the addition of high-intensity interval cycling to resistance training. This is in concert with recent data showing that the molecular signaling toward muscle hypertrophy are not blunted when high-intensity interval cycling follows acute resistance exercise (Pugh et al., 2015). Furthermore, it seems that cycling exercise may provide an additional stimulation for muscle growth when combined with resistance exercise (Kazior et al., 2016). Muscle strength increased similarly after RE and REC which is in agreement with previous studies showing that strength increments are not impeded with the addition of aerobic exercise on a bicycle to resistance exercise (McCarthy et al., 2002; Hakkinen et al., 2003). Resistance training-induced increases in muscle strength are principally attributed to muscle hypertrophy and neural adaptations. While the neural adaptations were not evaluated here, it may be postulated that since muscle strength and hypertrophy increased in parallel with both RE and REC, neural adaptations might also be comparable between the two training interventions. The addition of high-intensity cycling to resistance exercise prompted significant cardiovascular and local muscle adaptations leading to improved aerobic power as also found in most previous studies showing that resistance exercise does not inhibit aerobic power adaptations expressed either as VO$_2$max, maximal aerobic power or time to exhaustion (Kraemer et al., 1995; Bell et al., 2000; Hakkinen et al., 2003; de Souza et al., 2013; Cantrell et al., 2014). Moreover, vastus lateralis capillaries per fiber were significantly increased only after REC, which is in agreement with a previous report showing an increase in muscle capillarity after a 12-week training only in the concurrent strength and endurance training group (Bell et al., 2000). Thus, the present data suggest that high-intensity interval bicycling performed after resistance exercise may not inhibit resistance training-induced increases in muscle strength and mass but at that same time induce significant increases in aerobic capacity and local aerobic muscle environment.

Although the statistical analysis shows that muscle strength and hypertrophy were not inhibited with the addition of high-intensity aerobic training, a thought-provoking finding is worth mentioning: vastus lateralis CSA increased more after RE compared to REC. Also, a negative correlation was found between the percent increase in vastus lateralis CSA and the percent change in capillary density ($r = -0.521$, $P = 0.022$), suggesting that local muscle endurance–aerobic adaptations may have overpowered muscle hypertrophy in vastus lateralis in response to REC. Vastus lateralis muscle fiber CSAs were increased in response to RE (I: 14%, IIA: 18%, IIX: 23%) but this increase was somewhat smaller after REC (I: 10%, IIA: 15%, IIX: 21%), although not significantly different. Similarly, Hakkinen et al. (2003), reported larger increases in the CSA of all muscle fiber types after 21 weeks of strength training per se (I: 46%, IIA: 26%, IIX: 39%) compared with concurrent training (I: 13%, IIA: 23%, IIX: 31%), although not significantly different. Taken together, these data might suggest a minor, yet existing, interference between resistance training and high-intensity aerobic interval training, regarding muscle hypertrophy. Longer training periods might reveal a stronger interference between these two types of training which, however, needs further investigation since it might have practical applications for well-trained athletes.

Isometric leg press early rate of force development (50 ms), and impulse at 50, 100, and 150 ms decreased significantly after REC. Similar results were observed by Hakkinen et al. (2003), who reported a tendency for a decrease in maximal rate of force development after concurrent resistance and moderate intensity aerobic-cycling training. The increase in muscle strength and mass found in both groups in the current study cannot explain this decrease in the rate of force development. Also, the
fact that both RE and REC led to a decrease in type IIx muscle fiber composition may not explain the opposite adaptations in the rate of force development between two training types. It cannot be excluded that the decrease in early RFD here may be the result of the higher initial early RFD in REC compared to RE. Nevertheless, previous studies have proposed a possible link between the rate of force development and muscle architecture, especially the fascicle length: longer fascicle length is thought to be related with higher rates of force development (Zaras et al., 2016). Significant correlations were found between fascicle angle and RFD at 50, 100, 150 ms, as well as Impulse at all times \( r = -0.54 \) to \(-0.46\), \( P = 0.012-0.036 \) while fascicle angle was significantly increased only after REC (14%). Five weeks of concurrent strength and endurance training also resulted in fascicle angle increase and fascicle length decrease in soccer players (Enright et al., 2015). It has been postulated that muscles with large angles and shorter fascicles may generate force with less metabolic cost; such an adaptation might be expected with endurance training (Blazevich, 2006). Indeed, elite distance runners have greater fascicle angle in vastus lateralis and gastrocnemius medialis than elite sprinters and untrained men (Abe et al., 2000). Therefore, the increase in fascicle angle together with the (non-significant) decrease in fascicle length found after REC may be linked with enhancement of the local/muscle aerobic potential which might have led to diminished rate of force development, although this concept needs further investigation.

Resistance exercise aiming for increases in muscle strength/mass results in decreased numbers of type IIX muscle fibers which is usually accompanied by concomitant increases in IIA muscle fibers (Staron et al., 1994; Fry, 2004). In the current study, both RE and REC induced significant decreases in the number of type IIX fibers which is consistent to those previous data. Training parameters seem to dictate the exact muscle fiber adaptations since it was recently reported that continuous and interval endurance cycling performed immediately before resistance training may result in decreases in the percentage of type I fibers with concomitant increases in their CSA (Kazior et al., 2016). The underlying mechanisms toward such fiber type alterations should be the focus of future research.

High-intensity interval training on the bicycle ergometer was performed after resistance training in this study. Pilot measurements revealed that the participants could not sustain a high-resistance training intensity when this intense aerobic stimulus preceded resistance training. It cannot be excluded that the current results could be different perhaps due to different myofiber molecular milieu if aerobic exercise was performed first although acute molecular data suggest that signaling toward muscle hypertrophy would be of similar magnitude independent of the order of training (Apró et al., 2013). Moreover, muscle strength and mass of the individuals participated in the current study might have influenced the results since it is anticipated that strength-trained athletes may not demonstrate such large changes in muscle strength and morphology.

**Conclusion**

The present findings suggest that high-intensity interval cycling performed after heavy-resistance exercise does not inhibit resistance exercise-induced muscle strength and hypertrophy, while it prompts cardiovascular and local muscle adaptations leading to improved aerobic capacity. However, it seems that the addition of aerobic stimulus after heavy-resistance exercise may compromise the rate of force development, perhaps due to muscle architectural structure changes.

**Perspectives**

The majority of sports call for a combination of cardiovascular endurance and muscular strength in order to achieve elite performance. The current results suggest that muscle mass and strength may be developed effectively when high-intensity interval cycling at 100% of maximal aerobic power is performed after heavy-resistance exercise, two times per week. This may have practical applications also for individuals seeking health related improvements in muscular strength and hypertrophy as well as cardiovascular endurance, but they have limited time to spend on exercise training. Local muscle endurance adaptations may also be anticipated with such intervention. However, when the main training goal is to maximize the rate of force development, this form of concurrent training should be avoided.

**Key words:** Concurrent training, high-intensity interval training, aerobic capacity.

**Acknowledgements**

We express our gratitude to all participants in this study.

**Supporting Information**

Additional Supporting Information may be found online in the supporting information tab for this article:

**Figure S1.** Original representative force-time curve graph.

**Table S1.** Reliability of measures.
References


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