Single-leg cycle training is superior to double-leg cycling in improving the oxidative potential and metabolic profile of trained skeletal muscle

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Abbiss CR, Karagounis LG, Laursen PB, Peiffer JJ, Martin DT, Hawley JA, Fatehee NN, Martin JC. Single-leg cycle training is superior to double-leg cycling in improving the oxidative potential and metabolic profile of trained skeletal muscle. J Appl Physiol 110: 1248–1255, 2011. First published February 17, 2011; doi:10.1152/japplphysiol.01247.2010.—Single-leg cycle training may enhance the peripheral adaptations of skeletal muscle to a greater extent than double-leg cycling. The purpose of the current study was to determine the influence of 3 wk of high-intensity single- and double-leg cycle training on markers of oxidative potential and muscle metabolism and exercise performance. In a crossover design, nine trained cyclists (78 ± 7 kg body wt, 59 ± 5 ml·kg−1·min−1 maximal O2 consumption) performed an incremental cycling test and a 16-km cycling time trial before and after 3 wk of double-leg and counterweighted single-leg cycle training (2 training sessions per week). Training involved three (double) or six (single) maximal 4-min intervals with 6 min of recovery. Mean power output during the single-leg intervals was more than half that during the double-leg intervals (198 ± 29 vs. 344 ± 38 W, P < 0.05). Skeletal muscle biopsy samples from the vastus lateralis revealed a training-induced increase in Thr172-phosphorylated 5′-AMP-activated protein kinase α-subunit for both groups (P < 0.05). However, the increase in cytochrome c oxidase subunits II and IV and GLUT-4 protein concentration was greater following single- than double-leg cycling (P < 0.05). Training-induced improvements in maximal O2 consumption (3.9 ± 0.6 vs. 0.6 ± 3.6%) and time-trial performance (1.3 ± 0.5% vs. 2.3 ± 4.2%) were similar following both interventions. We conclude that short-term high-intensity single-leg cycle training can elicit greater enhancement in the metabolic and oxidative potential of skeletal muscle than traditional double-leg cycling. Single-leg cycling may therefore provide a valuable training stimulus for trained and clinical populations.

high-intensity interval training; oxidative enzyme activity; peroxisome proliferator-activated receptor-γ coactivator-1; protein content; exercise performance

ENDURANCE TRAINING leads to improvements in the metabolic profile and oxidative capacity of human skeletal muscle (19). Such improvements are associated not only with enhanced athletic performance (26), but also with a lowered risk of development of chronic disease states (17). High-intensity interval training, consisting of repeated exercise bouts performed close to or above the maximal O2 consumption (V̇O2max), interspersed with low-intensity exercise or complete rest (26), elicits metabolic adaptations similar to those obtained after more “traditional” prolonged low- or moderate-intensity exercise (4, 14), at least after short-duration (≤6 wk) training interventions. For instance, 2–6 wk of high-intensity interval training (4–6 repeats of 30-s “all-out” cycling 3 times per week) results in increases in muscle buffering capacity, protein content of mitochondrial cytochrome c oxidase (COX) subunits II and IV (14), and peroxisome proliferator-activated receptor-γ coactivator (PGC-1) (4) in skeletal muscle of recreationally active humans similar to those observed in traditional low-intensity endurance training, despite a lower training-associated energy cost. Furthermore, high-intensity interval training has been shown to downregulate the silent mating-type information regulator 2 homolog 1 (SIRT1) following high-intensity interval training, despite its increased activity (16). SIRT1 has been implicated as a mediator of PGC-1-dependent mitochondrial biogenesis (12). In addition, contractile activity has been shown to increase 5′-AMP-activated protein kinase α-subunit (AMPKα) phosphorylation (Thr172) and activity, resulting in increased glycogen content in muscle (23).

A limitation associated with performing high-intensity interval training is that such exercise may be limited by central (i.e., cardiovascular and hematoletic parameters), rather than peripheral (i.e., respiratory capacity of the working muscles), physiological factors (9, 31, 38). Training for prolonged periods at high exercise intensities (i.e., at or above V̇O2max) may also be difficult for certain individuals or patient populations, resulting in reduced skeletal muscle adaptations and, possibly, compromised gains in prolonged athletic performance (i.e., metabolic thresholds and sustained exercise intensity) (9, 31, 39), glucose tolerance in diabetic patients (22), and quality of life in cardiac disease patients (33). Methods of increasing central delivery of oxygenated blood include hyperbaric or hypoxic therapies, which can acutely increase V̇O2max, thereby permitting a higher exercise intensity to be performed and, thus, enhancing peripheral muscular respiratory adaptations (36, 37). Nevertheless, the application and effectiveness of this technique may be limited by cost and the relatively small increase in V̇O2max that typically occurs (37). An alter-
native approach to reduce central limitations (i.e., oxygenated blood supply) that can occur during interval training would be to exercise a smaller muscle mass (40), e.g., to train only one leg at a time. During normal bilateral cycling, each active leg consumes approximately half of the total $\text{O}_2$ uptake (neglecting the cost of unloaded cycling) to produce half of the power delivered to the bicycle’s rear wheel. Consequently, the musculature of the legs must have the respiratory capacity to process $\leq$50% of the total maximum supply of oxygenated blood. During single-leg cycling, however, the reduced $\text{O}_2$ uptake of the inactive leg allows the active muscles to be potentially supplied with significantly more oxygenated blood (24). This exercise modality manipulation increases the single-leg exercise intensity (3) and may, in turn, elicit further adaptations with regular exercise training.

The purpose of this study was to compare the effects of a short-duration (3 wk) high-intensity single- and double-leg cycle-training program on exercise capacity, performance, and markers of oxidative potential and muscle metabolism. We hypothesized that single-leg cycle training would enable a greater exercise load to be achieved peripherally and elicit greater adaptive responses (i.e., increases in oxidative enzyme activity, greater protein levels, and superior exercise performance) than double-leg cycle training.

METHODS

Participants

Nine trained cyclists (34 $\pm$ 5 yr old, 181 $\pm$ 7 cm stature, 78 $\pm$ 7 kg body wt, 59 $\pm$ 5 ml·kg$^{-1}$·min$^{-1}$ $\text{V}O_{2\text{max}}$) with $\geq$2 yr of cycling experience were recruited for the study. Participants were informed about the procedures and risks associated with their participation in the study. Prior to data collection, written informed consent was obtained from the participants, and the study protocol and procedures were reviewed and approved by the Human Research Ethics Committee at Edith Cowan University. Throughout the duration of the study, participants were requested to maintain regular training commitments and to refrain from demanding exercise in the 24-h period prior to an experimental trial. Furthermore, external training commitments were monitored in the week prior to and during the first 3-wk training period ($\leq$50% of the total maximum supply of oxygenated blood. During single-leg cycling, however, the reduced $\text{O}_2$ uptake of the inactive leg allows the active muscles to be potentially supplied with significantly more oxygenated blood (24). This exercise modality manipulation increases the single-leg exercise intensity (3) and may, in turn, elicit further adaptations with regular exercise training.

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Protocol/Training

In a randomized crossover design, participants completed six bouts of high-intensity single- and double-leg cycle training (Fig. 1) over a period of 21 days. Single- and double-leg training was separated by a 42-day washout period (Fig. 1B). All cycle training was conducted on an electromagnetically braked cycle ergometer (Velotron, RacerMate, Seattle, WA) under supervision. During double-leg training, participants used a standard bilateral pedaling technique, while single-leg training sessions involved two bouts (one on each leg) of single-leg cycling. When cycling with only one leg, the rider must typically “pull up” once the pedal reaches bottom dead center. This requires recruitment of the less powerful and more fatigable hip flexor muscle group, a situation that can be uncomfortable and limits the maximal exercise intensity that can be attained. During single-leg cycling, a counterweight system was therefore fitted to the contralateral pedal on the Velotron cycle ergometer; this system assisted with the upward phase of the pedaling action, thus preserving normal double-leg cycling biomechanics (43).

Each double-leg training session required participants to perform a total of three maximal self-paced 4-min intervals with 6 min of active recovery (100 W). Similarly, single-leg training involved three maximal self-paced 4-min intervals with 6 min of active recovery (50 W) on one leg. This was followed by the identical protocol completed on the opposite leg. During each interval, participants were provided with continuous feedback for power output and were instructed to perform each 4-min interval at the highest average power output they could sustain. Previous work (34) and our own pilot data indicated that the training protocol used in this study (i.e., 4-min interval) maximized the time that athletes could spend at power outputs that elicited $\text{V}O_{2\text{max}}$ and, therefore, increase the likelihood that performance during double-leg cycling would be limited centrally. The present methodology also ensured that the total time exercising each leg was consistent between single- and double-leg cycle training (i.e., similar number of muscular contractions). The initial leg used during single-leg cycling and the order of experimental trials (single- vs. double-leg cycling) were randomized and semicounterbalanced.

Heart rate was recorded throughout all training sessions (Polar S810, PolarElecto, Kemple, Finland), while rating of whole body perceived exertion (Borg’s RPE scale, 6–20 points), pain intensity in the quadriceps (6), and perception of effort as a percentage of maximal effort (i.e., 0–100%) were assessed following each interval. For comparisons, average power output and heart rate, as well as rating of perceived exertion, pain, and effort were averaged over the entire 3 wk of single- and double-leg training. Work completed during all single- and double-leg intervals was calculated based on the following formula: work ($J$) = $P \times t$, where $P$ is the average power output ($W$) produced during the intervals and $t$ is the total time (s).
performing intervals (i.e., 6 sessions × 3 intervals per session × 4 min per interval). Total work completed during single-leg cycling was calculated as the sum of the right and left legs.

**Performance Tests**

In the week prior to and following the training interventions, participants performed an incremental cycling test to exhaustion and a self-paced 16.1-km cycling time trial on a Velotron cycle ergometer using a typical bilateral cycling technique. The incremental cycling test and time trial were performed on separate days (≥2 days apart) and in standardized laboratory conditions (16–18°C, 40–50% relative humidity). During the incremental cycling tests, resistance started at 100 W for 5 min, with intensity increased by 50 W every 5 min until volitional fatigue or a cadence of ≥60 rpm could not be maintained by the participant. Throughout the incremental cycling tests, gas exchange was assessed using a verified (15) respiratory gas analyzer (ParvoMedics, TrueOne, Sandy, UT). Prior to the tests, the gas analyzer was calibrated using alpha gases of known concentrations, and the ventilometer was calibrated using a 3-liter syringe (Hans Rudolph, Kansas, MO). The determination of maximal aerobic power and \( \text{VO}_{2\text{max}} \) was as previously described (2). \( \text{O}_2 \) consumption, \( \text{CO}_2 \) production, and respiratory exchange ratio averaged over the final 60 s of the 200-W stage during the incremental cycling test were used to calculate cycling economy (\( W^{-1} \cdot \text{min}^{-1} \)) and gross mechanical efficiency (%), as previously described (30). During the incremental cycling test, blood lactate concentration (LactatePro, Kyoto, Japan) was determined at completion of each workload and used to determine lactate threshold, as previously described (32).

During the 16.1-km cycling time trials, participants were instructed to complete the distance in the fastest time possible. Before each time trial, a standardized 10-min warm-up consisting of 3 min at 25%, 5 min at 60%, and 2 min at 80% of maximal aerobic power was performed. During the time trials, participants were free to alter pedaling cadence and gear ratio as required. Power output was sampled at a rate of 1 Hz throughout the trial; however, the only feedback provided to the participants was the distance completed. A fan was placed directly in front of the participant and provided a wind speed similar to that experienced during outdoor cycling (32 km/h) (41). Throughout the trials, water intake was ad libitum.

**Muscle Biopsy**

In the week prior to the first training session and 72 h following the final training session, muscle biopsy samples were obtained from the belly of the vastus lateralis by standard percutaneous needle biopsy techniques with suction applied (18). Participants were asked to consume a similar diet in the 24-h period preceding the biopsy procedure and to refrain from exercise for 48 h prior to the procedure. For the biopsy procedure, participants rested in a supine position, and a local anesthetic (1% xylocaine) was injected into the skin and subcutaneous tissue above the belly of the vastus lateralis. Then a small incision was made through the skin and fascia. A standardized needle biopsy technique (18) was used to extract subcutaneous tissue above the belly of the vastus lateralis. Then a

**Analytical Procedures**

**Protein analysis.** Muscle samples were homogenized in 700 μl of ice-cold buffer (50 mM Tris-HCl, pH 7.5, 1 mM EDTA, 1 mM EGTA, 10% glycerol, 1% Triton X-100, 50 mM NaF, 5 mM Na pyrophosphate, 1 mM DTT, 10 μg/ml trypsin inhibitor, 2 μg/ml aprotinin, 1 mM benzamidine, and 1 mM phenylmethylsulfonyl fluoride) at a dilution of 1:10 (~70 mg of muscle per 700 μl of buffer). The lysate was centrifuged at 12,000 × g for 20 min at 4°C. Protein concentrations were determined using a bicinchoninic acid protein measurement kit (Pierce, Rockford, IL).

**Western blotting.** Twenty micrograms of protein were separated using 10 or 12% SDS-PAGE and subsequently transferred to polyvinylidene difluoride membranes (Bio-Rad, Hercules, CA). Membranes were blocked with 5% nonfat milk-Tris-buffered saline + Tween 20 (TBST) for 90 min. All primary antibodies, except α-tubulin, were incubated overnight at 4°C in TBST at a 1:1,000 dilution; α-tubulin was diluted at 1:2,000. Membranes were washed (5 times for 5 min) with TBST and incubated with secondary antibody for 60 min at room temperature (1:2,000 dilution). The membranes were washed again (5 times for 5 min) with TBST and then exposed and visualized by chemiluminescence and quantified by densitometry (Chemidoc, Bio-Rad). All densitometry values were expressed relative to a corresponding α-tubulin control from the equivalent sample lysate. For Thr\(^{172}\) phosphorylated AMPKα, results are expressed as the ratio of phosphorylated to total protein content after correction for α-tubulin.

**Statistical Analysis**

Power output, total work, heart rate, rating of perceived exertion, pain, and effort averaged over all single- and double-leg training sessions were compared using paired-sample t-tests. The influence of training on dependent variables (i.e., maximal aerobic power output, cycling economy, gross efficiency, power output at lactate threshold, average time-trial power output, and muscle biopsy variables) was analyzed using a two-way repeated-measures ANOVA. Where significant effects were observed, Newman-Keuls post hoc test was used. Assumptions of normality (Kolmogorov-Smirnov test) and sphericity (Mauchly’s test) were assessed. Where violations of assumptions of sphericity were observed, the degrees of freedom were corrected using Greenhouse-Geisser or Huynh-Feldt corrections where appropriate. To further delineate differences in performance (time trial and maximal aerobic power output), the percent change in power in each condition was compared with the smallest worthwhile performance difference (1.0%) calculated from previously published coefficient of variation measurements of sustainable power during a time trial using the Velotron cycle ergometer (1, 21, 42). The probability of the true effect being beneficial, trivial, or harmful was determined (20). Critical level of significance was established at \( P < 0.05 \). Results are presented as means ± SD (unless otherwise stated).

**RESULTS**

**Training**

All participants performed all single- and double-leg cycle-training sessions. Average power output during single-leg intervals was 58.3 ± 3.7% of that during double-leg intervals (Table 1). Average power output during the double-leg intervals was 102 ± 5% of maximal aerobic power output. As a result, significantly more total work was performed during single- than double-leg training (1,714.4 ± 246.5 vs. 1,486.5 ± 162.4 kJ, \( P < 0.05 \); Table 1). Rating of perceived exertion was lower (16 ± 2 vs. 18 ± 1, \( P < 0.05 \)) during single-leg training, whereas quadriceps pain (8 ± 3 and 7 ± 1) and effort (95 ± 4 and 95 ± 3) were similar during single- and double-leg training, respectively. Average heart rate throughout the 4-min intervals was significantly higher during double-leg (164 ± 8 beats/min, 91.1 ± 2.6% maximal heart rate) than single-leg (145 ± 9 beats/min, 80.0 ± 4.5% maximal heart rate) training. Peak heart rate was also significantly higher during double-leg (180 ± 8 beats/min, 97.0 ± 4.3% maximal heart rate) than
single-leg (168 ± 12 beats/min, 90.3 ± 6.7% maximal heart rate) intervals.

Performance Tests

Prior to training, maximal aerobic power output (328 ± 36 vs. 338 ± 31 W, \(P = 0.34\)), \(\dot{V}O_2\)max (59.5 ± 5.4 vs. 57.4 ± 4.4 ml·kg\(^{-1}\)·min\(^{-1}\), \(P = 0.12\)), cycling economy (73.5 ± 4.1 vs. 72.0 ± 4.2 W·l\(^{-1}\)·min\(^{-1}\), \(P = 0.33\)), gross cycling efficiency (21.3 ± 1.3 vs. 20.9 ± 1.2%, \(P = 0.60\)), power output at lactate threshold (246 ± 41 vs. 245 ± 34 W, \(P = 0.54\)), and average time-trial power output (305 ± 30 vs. 295 ± 35 W, \(P = 0.89\)) were similar between single- and double-leg cycling. Maximal aerobic power output tended to be greater following single-leg (3.9 ± 6.2%, \(P = 0.09\)) compared with double-leg (0.6 ± 3.6%, \(P = 0.61\)) training (Fig. 2A). The likelihood that the true change in maximal aerobic performance following single-leg cycling was practically beneficial/trivial/harmful compared with double-leg cycling was 61/32/7%.

Muscle Protein Content

GLUT-4 protein expression significantly increased following single-leg, but not double-leg, cycle training (Fig. 3A). GLUT-4 protein concentration was significantly greater following single- than double-leg cycle training (Fig. 3A). Similarly, AS160 protein expression significantly increased as a result of single-leg, but not double-leg, training (Fig. 3B). Phosphorylation of AMPK\(\alpha\) at Thr\(^{172}\) significantly increased following single- and double-leg cycle training (Fig. 4A). Total

Table 1. Average power output and total work calculated from all single- and double-leg intervals performed over the 3-wk training intervention

<table>
<thead>
<tr>
<th>Condition</th>
<th>Average Power, W</th>
<th>Average Power per Leg, W</th>
<th>No. of Sessions</th>
<th>Intervals per Session</th>
<th>Time per Interval, min</th>
<th>Total Work, kJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-leg</td>
<td>198 ± 29</td>
<td>198 ± 29</td>
<td>6</td>
<td>3 × 2</td>
<td>4</td>
<td>1,714.4 ± 246.5</td>
</tr>
<tr>
<td>Double-leg</td>
<td>344 ± 38</td>
<td>172 ± 19*</td>
<td>6</td>
<td>3</td>
<td>4</td>
<td>14,86.5 ± 162.4*</td>
</tr>
</tbody>
</table>

Values are means ± SD of average power output, average power output per leg, and total work during single- and double-leg training. *\(P < 0.05\) vs. single-leg.
SIRT1 content was not significantly different following single- or double-leg cycle training ($P < 0.07$; Fig. 4B). PGC-1 protein content was not different following single- or double-leg cycling (Fig. 5A). Nevertheless, COX II and IV protein content was significantly greater following single- than double-leg cycle training (Fig. 5, B and C).

**DISCUSSION**

The purpose of this study was to examine the effect of a short-term cycling interval training program completed using one or two legs on exercise capacity, performance, and markers of oxidative potential and muscle metabolism. One of the novel features of our study was the use, during single-leg training, of a counterweight system on the opposing crank that permitted similar muscle recruitment patterns but higher individual leg power outputs than during double-leg cycling. Major findings from this study are as follows: 1) improvements in mitochondrial oxidative capacity and glucose transport potential of already trained human skeletal muscle were significantly greater after single- than double-leg cycling; 2) despite the higher individual leg workloads achieved during single-leg cycle training, participants reported lower perceived exertion and similar perceptions of effort and quadriceps pain; and 3) maximal aerobic capacity and prolonged time-trial performance were unaffected by single- or double-leg training.

To the best of our knowledge, this is the first study showing significantly greater improvements in cellular glucose transport (i.e., GLUT-4 protein, AS160 protein) and mitochondrial oxidative capacity (i.e., COX II and IV) of skeletal muscle following single-leg compared with normal bilateral cycle training. It is likely that the increases in the metabolic potential of skeletal muscle were the result of higher individual leg power outputs achieved during the single-leg cycle training (Table 1). An
increase in blood flow to the exercising limb has been observed during single- compared with double-leg cycling (24). It is therefore possible that the increases in skeletal muscle glucose transport capacity and mitochondrial oxidative potential following single-leg cycle training were due in part to greater muscle blood flow and \( O_2 \) delivery to the exercised muscle. The high power outputs attained during single-leg cycling were most likely enabled by the counterweight system, which preserves normal cycling biomechanics (43), reducing hip-flexor fatigue. The potential mechanisms by which low-volume high-intensity exercise enhances glucose transport and promotes mitochondrial biogenesis are not completely understood (7). It is possible that high-intensity exercise activates kinases involved in insulin-independent (i.e., muscle contraction-mediated) GLUT-4 and mitochondrial gene transcription (e.g., \( Ca^{2+}/ \) calmodulin-dependent protein kinase and AMPK) to a greater extent than lower-intensity exercise (11, 25). Nevertheless, the increase in Thr\(^{172} \) phosphorylation of AMPK\( \alpha \) in the present study was not significantly different between single- and double-leg cycling. Furthermore, SIRT1 protein content did not change following single- or double-leg training. Similar to AMPK, SIRT1 has been implemented as a metabolic stress sensor that directly connects metabolic permutations with PGC-1 transcriptional activity (5). AMPK is thought to be, in part, responsible for the phosphorylation of AS160, which may signal GLUT-4 translocation and subsequent uptake of glucose into skeletal muscle cells (10). In the present study, AS160 and GLUT-4 protein were significantly increased following single-leg, but not double-leg, cycle training, yet whole muscle content of the transcriptional coactivator PGC-1, which is involved in coordinating GLUT-4 and mitochondrial gene transcription, was not significantly different following single- or double-leg cycling (Fig. 5A). It is therefore probable that PGC-1 activation and translocation to the nucleus, rather than an upregulation of PGC-1 protein content per se, accounted for the adaptive response observed in this study (29). In support of this premise, a number of studies have observed enhanced oxidative potential of human skeletal muscle (i.e., increased citrate synthase, COX II, and COX IV) following short-term training that preceded upregulation of PGC-1 protein and coincided with PGC-1 translocation to the nucleus (29, 44).

The improvements in oxidative potential and metabolic profile of skeletal muscle observed in this study are somewhat larger than those previously observed following low-volume high-intensity interval training. Such differences may be due to differences in the study participants. The present experiments utilized trained cyclists, whereas untrained cyclists were used in the majority of previous studies of metabolic changes in skeletal muscle due to high-intensity training (4, 14, 29). It is therefore possible that the greater physiological adaptations observed in this study are the result of higher workloads achieved by the trained participants. Furthermore, differences between the results of this and previous research (4, 14) may be due to the longer (4 min vs. 30 s) interval durations performed in this study, thus placing a greater demand on oxidative metabolism. Finally, all intervals in the present study were performed “maximally,” so as to achieve the greatest intensity possible during the training sessions. To control the total work completed, previous studies using long interval durations (>30 s) have typically restricted power output during the intervals (i.e., 90–100% of \( \dot{V}O_{2\text{max}} \)) (27, 29, 35). Exercise intensity in the current study was perceived as maximal for single- and double-leg cycle training. However, there was a greater mechanical and metabolic load during the single-leg condition, which is the most likely contributor to the superior skeletal muscle adaptations associated with the single-leg training. Further research is needed to ascertain if similar adaptations may be possible with short-duration near-maximal single-leg cycling intervals (i.e., 30 s).

Studies comparing prolonged moderate-intensity endurance cycling with short-duration high-intensity interval training have shown similar adaptations between treatment interventions (4, 14). Gibala (13) concluded that high-intensity interval training is therefore an effective and time-efficient strategy for improving metabolic function and, potentially, lowering chronic disease risk factors. A major limitation of high-intensity interval training, however, is that it typically involves all-out or extremely high efforts, which can result in feelings of nausea and extreme discomfort. Furthermore, high-intensity interval training can place participants at an increased risk of a cardiovascular episode due to the additional strain it places on the cardiovascular system (i.e., maximal or near-maximal cardiac output). Therefore, although high-intensity interval training can be time-efficient, it may be impractical or unsuitable for the general population (8, 29) and/or patients at risk of succumbing to a cardiovascular episode. To overcome this, Little et al. (29) recently examined metabolic adaptations and exercise performance in untrained individuals following 2 wk of interval training (i.e., 8–12 × 60-s intervals) performed at 100% maximal aerobic power output, rather than all-out exercise intensities. They found that GLUT-4 protein content and nuclear abundance of PGC-1 were significantly increased following training (29). In the present study, despite the significantly greater individual leg power output during single-leg cycle training (Table 1), ratings of whole body perceived exertion were lower than during double-leg cycling, and quadriiceps pain and perceived effort were similar during single- and double-leg cycling. It is possible that the lower perceived exertion during the single-leg cycle training could improve training program adherence compared with traditional high-intensity intervals (28). However, it should also be noted that single-leg cycling requires participants to exercise each leg independently; therefore, each training session is twice the duration of the double-leg training. It is possible that the longer trial duration may impact training program adherence. As evidenced by the significantly lower average and peak heart rates achieved in single-leg cycle training, this form of training is also likely to incur a lower level of cardiovascular stress. Such a finding suggests that this form of training may also be beneficial for enhancing peripheral adaptations in “at-risk” cardiovascular patients.

Despite improvements in the oxidative potential of skeletal muscle observed in the present study, maximal aerobic power output, \( \dot{V}O_{2\text{max}} \), cycling efficiency, gross cycling economy, power output at lactate threshold, and time-trial performance were not significantly different following single- or double-leg cycle training. This is in contrast to previous research showing improvements in cycling time-trial performance following 2 wk of high-intensity interval training in recreationally active or untrained participants (14, 29). Laursen et al. (27) reported increases in \( \dot{V}O_{2\text{max}} \) and 40-km time-trial performance in well-trained cyclists after 4 wk, but not 2 wk, of high-intensity

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interval training. Further research is needed to determine if a longer training period (i.e., 4–6 wk) might result in improvements in exercise performance with single-leg cycling in trained athletes. Indeed, a “possible” beneficial effect (61%) on maximal aerobic power output was observed in the present study following single-leg, compared with double-leg, cycling. Consequently, it is unclear from the results of this study if single-leg cycling improves exercise performance in trained participants above that of traditional double-leg cycling. In addition, the efficacy of assisted single-leg cycling as a training intervention in clinical populations (i.e., cardiovascular rehabilitation and diabetic patients) warrants further investigation.

In conclusion, the novel finding from the present study was that counterweighted single-leg cycling allowed trained cyclists to produce higher individual leg power outputs and, thus, more work during “maximal” high-intensity interval training than traditional double-leg cycle training. This assisted high-intensity single-leg interval training performed over 2 wk (6 sessions) resulted in significant improvements in the metabolic and oxidative potential of skeletal muscle in trained cyclists. Finally, despite the higher power outputs achieved during the single-leg cycle training, participants reported a lower perceived exertion and similar pain intensity in the quadriceps. Assisted single-leg cycling may therefore provide a valuable training stimulus for inducing peripheral adaptations in trained and clinical populations. However, future studies are needed to examine longer training intervention periods and the effects of such interventions across a variety of healthy and diseased populations.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

REFERENCES


