Potential for strength and endurance training to amplify endurance performance

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JIIICKSON, R. C., B. A. DVORAK, E. M. GOROSTIAGA, T. T. KUROWSKI, AND C. FOSTER. Potential for strength and endurance training to amplify endurance performance. J. Appl. Physiol. 65(5): 2285-2290, 1988.—The impact of adding heavy-resistance training to increase leg-muscle strength was studied in eight cycling- and running-trained subjects who were already at a steady-state level of performance. Strength training was performed 3 days/wk for 10 wk, whereas endurance training remained constant during this phase. After 10 wk, leg strength was increased by an average of 30%, but thigh girth and biopsied vastus lateralis muscle fiber areas (fast and slow twitch) and citrate synthase activities were unchanged. Maximal O2 uptake was increased by an average of 30%, but thigh girth and biopsied vastus lateralis muscle fiber areas (fast and slow twitch) and citrate synthase activities were unchanged. Maximal O2 uptake (\(\overline{V}O_2\)max) was also unchanged by heavy-resistance training during cycling (55 ml·kg\(^{-1}\)·min\(^{-1}\)) and treadmill running (60 ml·kg\(^{-1}\)·min\(^{-1}\)); however, short-term endurance (4-8 min) was increased by 11 and 13% (\(P < 0.05\)) during cycling and running, respectively. Long-term cycling to exhaustion at 80% \(\overline{V}O_2\)max increased from 71 to 85 min (\(P < 0.05\)) after the addition of strength training, whereas long-term running (10 km times) results were inconclusive. These data do not demonstrate any negative performance effects of adding heavy-resistance training to ongoing endurance-training regimens. They indicate that certain types of endurance performance, particularly those requiring fast-twitch fiber recruitment, can be improved by strength-training supplementation.

However, one of the unresolved questions in the area of evaluating the interrelationships of these two methodologies is the influence of strength training on endurance performance. Along these lines, it is known that strength types of training do not increase maximal O2 uptake to nearly the same extent as endurance training (1, 9, 14, 17, 18, 22, 28), and the endurance training-associated increases in maximal O2 uptake do not appear affected by a strength program (14). Nevertheless, in an earlier study from this laboratory (17), it was found that in untrained subjects who had increased the strength of their lower extremities, time to exhaustion was enhanced during high-intensity, short-duration (4-8 min) cycling and treadmill running exercise. By contrast, one of the adaptations to strength types of exercise is the enlargement of the trained muscles (7, 20, 26, 27). This added mass could negate the positive effects of the strength improvement, particularly during exercise of long duration (230 min). These observations provided the impetus to further determine, in greater detail, whether strength training produces positive or negative effects on both short- and, in particular, long-term performance in subjects already well trained in cycling and running.

**METHODS**

**Subjects and experimental design.** Eight subjects, six males and two females ([\(\overline{V}O_2\)max] maximal O2 uptake \(\geq 50\) ml·kg\(^{-1}\)·min\(^{-1}\)], volunteered to participate in the study. The subjects' ages, heights, and weights, as well as their previous training history, are shown in Table 1. Many of the subjects had been endurance-trained for several years. Before the start of testing for the strength phase of the study, all subjects had been training continuously for a minimum of 3-4 mo after a cycling-running (4-miles minimum distance) protocol that has been employed previously in this laboratory (cf. 14, 16). Previous training and injuries caused some minor modifications. **Subject B** had been running exclusively for many years. Therefore, rather than markedly alter this regime, cycling was included once per week to familiarize him with this type of exercise for the testing procedures. **Subject F** had a chronic leg problem that resulted in an adjustment in running to 20 min/day, 2 days/wk, and cycling was increased to 4 days/wk. All the subjects maintained constant training work rates a minimum of 6-8 wk before the initiation of strength training.

Because a major emphasis of this work was centered...
on the long-term performance results, the initial testing procedures were separated by 3-wk intervals. This aspect of the study was conducted to demonstrate that the subjects were in a steady-state level of performance with respect to these testing procedures before the initiation of the strength phase. These data are shown in Table 4 and are discussed later in relation to the long-term performance results.

**Strength training.** This program consisted of weight training 3 days/wk for 10 wk. The following exercises were performed: parallel squats, five sets of five repetitions; knee extensions, three sets of five repetitions; knee flexions, three sets of five repetitions, and toe raises, three sets of 25 repetitions. All exercises were performed with as much weight as possible. With the exception of the toe raises, this resistance initially was ~80% of the one-repetition maximum. As strength increased (i.e., performing more than five repetitions/set), additional weights were added to maintain this same relative resistance for the required repetitions. The sets were separated by 2-min rest periods. The parallel squats and toe raises were performed using Olympic-style weights, the knee flexions and extensions on a Universal gym. Strength training was always performed with 1 or 2 days rest between sessions and was completed ≥1 h before beginning endurance training. These times remained constant for each subject.

No strength training of the leg muscles had been performed at least 6 mo before the start of the strength phase. During the strength phase, each subject continued to endurance train at the same absolute cycling and running intensities that they had been performing for a minimum of 6–8 wk up to several years.

**Measurement of V̇O₂ max.** V̇O₂ max was measured during work on a cycle ergometer (Monark) and during work on a treadmill as described previously (16). For the V̇O₂ max tests, the subjects performed exercise bouts of 4- to 8-min durations against progressively increasing work loads. In general, for the cycling tests, the work rates were increased at 1-min intervals with the amount varying according to the subject’s exercise capacity, whereas for the treadmill tests, speed and/or grade were increased at 1-min intervals with the amount of work also varying according to each subject’s exercise capacity. There were a minimum of two tests per subject on the bicycle and treadmill. The criterion that V̇O₂ max showed no further increase (“leveling off”) or a decrease with increasing work loads was used to establish maximum values in all of the subjects before beginning strength training and after the 10-wk strength and endurance phase. During the V̇O₂ max tests, the subject’s expired air was continuously analyzed for volume, O₂, and CO₂ concentration with a Beckman Metabolic Measurement Cart.

**Measurement of strength.** Leg strength was assessed by determining the maximum amount of weight that could be lifted for one repetition in a parallel squat, knee extension, and knee flexion. The subjects were familiarized with all procedures before testing. They performed multiple single repetitions against increasing resistances with ~3–4 min elapsing between lifts. The criterion for determining strength was the inability to continue to perform a single repetition. These determinations were made several times before and at least once after the 10 wk of strength and endurance training. All tests were conducted by the same individual.

**Long-term endurance.** Cycling time to exhaustion was measured on a Schwinn ergometric exerciser (EX2) while pedaling against resistances that required 80–85% of the subject’s V̇O₂ max. The subjects were considered exhausted at the point at which they could not keep cycling at the preselected work rate. Running performance consisted of completing 10 km as fast as possible. To minimize

### Table 1. Physical characteristics and training history of subjects before start of strength phase

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age, yr</th>
<th>Sex</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>Previous Training</th>
<th>Total Training, yr</th>
<th>Current Training,* mo</th>
<th>Most Recent Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20</td>
<td>M</td>
<td>180.5</td>
<td>66.8</td>
<td>Soccer</td>
<td>5</td>
<td>4</td>
<td>Cycling 3 days/wk</td>
</tr>
<tr>
<td>B</td>
<td>33</td>
<td>M</td>
<td>188.0</td>
<td>75.9</td>
<td>Recreational</td>
<td>12</td>
<td>144</td>
<td>Running 3 days/wk</td>
</tr>
<tr>
<td>C</td>
<td>29</td>
<td>F</td>
<td>168.4</td>
<td>63.4</td>
<td>Running</td>
<td>12</td>
<td>144</td>
<td>Cycling 1 day/wk</td>
</tr>
<tr>
<td>D</td>
<td>39</td>
<td>M</td>
<td>191.5</td>
<td>86.5</td>
<td>Cycling</td>
<td>3</td>
<td>5</td>
<td>Running 5 days/wk</td>
</tr>
<tr>
<td>E</td>
<td>30</td>
<td>M</td>
<td>168.2</td>
<td>62.3</td>
<td>Running</td>
<td>11</td>
<td>15</td>
<td>Cycling 3 days/wk</td>
</tr>
<tr>
<td>F</td>
<td>30</td>
<td>M</td>
<td>178.8</td>
<td>69.3</td>
<td>Weight lifting</td>
<td>11</td>
<td>4</td>
<td>Cycling 3 days/wk</td>
</tr>
<tr>
<td>G</td>
<td>29</td>
<td>M</td>
<td>179.3</td>
<td>82.5</td>
<td>Running</td>
<td>6</td>
<td>3</td>
<td>Cycling 2 days/wk</td>
</tr>
<tr>
<td>H</td>
<td>30</td>
<td>F</td>
<td>167.5</td>
<td>63.0</td>
<td>Cycling</td>
<td>12</td>
<td>70</td>
<td>Cycling 3 days/wk</td>
</tr>
</tbody>
</table>

**Means ± SE**: 31.1±1.2 177.7±3.2 71.2±3.3

* Individual training schedule maintained without cessation before start of strength training.
Environmental conditions on performance, the 10-km testing was performed on an indoor track. Before the strength training, the subjects were tested at least twice on each measure to verify that their performances were not improving. Each subject ate the same food 2 days preceding and on the day of all long-term endurance tests. Time of day for testing was kept constant for each subject. No endurance training was performed the day before a long-term endurance test.

**Short-term endurance**. Each subject’s short-term endurance was measured while cycling (Monark) and running at maximal work rates that resulted in exhaustion within 5–8 min as described previously (17). Subjects were tested before the strength phase and at the same absolute intensities after the 10 wk of strength and endurance training. Blood samples were obtained from an antecubital vein 5 min postexercise. One milliliter of blood was deproteinized in 2 ml of 17.5% perchloric acid (PCA), centrifuged, and stored at −20°C until analysis. The PCA extracts were subsequently neutralized and analyzed for lactate (12).

**Skin fold and body fat analysis**. Thigh girth on each leg was measured at the midpoint from the greater trochanter to the superior border of the patella. Skin fold thickness was measured at the following sites: triceps, subscapula, suprailiac, pectoralis, anterior thigh, and axilla. Body density by underwater weighing was determined according to the procedures and calculations described by Pollock et al. (24). All measurements were made in the morning before any exercise and after at least a 12-h fast. Measurements were made within 2–3 days before the start of the strength phase, and again immediately after the 10–wk strength program.

**Muscle sampling and analyses**. Muscle samples (30–70 mg) from the lateral portion of the quadriceps muscles (vastus lateralis) were obtained from seven subjects at rest, both before and after the strength and endurance phase, according to the percutaneous needle biopsy procedure of Bergstrom (3). One portion was frozen in 2-methylbutane (isopentane), which had been precooled in a liquid N₂ bath and later stored at −80°C for histochemical analysis. The samples (~150 fibers/biopsy) were sectioned (10 μm) and stained histochemically for identification of slow-twitch and fast-twitch fibers by the myofibrillar adenosinetriphosphatase reaction using acid and alkaline preincubation (5). For fiber area determinations, the cross-sectional areas were projected (×240) onto white paper and traced. A minimum of twenty slow-twitch and twenty fast-twitch fibers were measured with a polar planimeter. Mean values were calculated per section and converted to square micrometers. Four of these samples were accidentally destroyed before analysis.

Another muscle portion was frozen in liquid N₂ and stored at −80°C until analyzed for citrate synthase activity (25). Protein content of these homogenates was determined by the Folin phenol method (19).

**Statistical procedures**. The data were analyzed using the Hotelling multivariate t test. Statistical significance was set at the 0.05 level.

**RESULTS**

**Effectiveness of the strength program**. Strength was increased by 27% in the parallel squats, 37% in knee extensions, and 25% in knee flexions (Fig. 1). For the three exercises, the overall strength gains averaged 30%.

**Total body and skeletal muscle effects**. After strength and endurance training, body weights remained the same as with endurance training alone (Table 1). There were no changes in body composition or thigh girth after the strength and endurance phase (Table 2). Vastus lateralis muscle fiber composition remained in the same range after strength and endurance training as before, and the lack of change in slow- or fast-twitch fiber areas support the overall thigh girth measurements (Table 2). Citrate synthase activities of the biopsied muscles also remained the same after compared with before the addition of strength training (Table 2).

**VO₂ max and short-term endurance**. By the criterion of VO₂ max, 55 ml·kg⁻¹·min⁻¹ during cycling and 60 ml·kg⁻¹·min⁻¹ during treadmill running, the subjects were considered well trained before incorporation of strength training into their exercise regimen (Table 3). The combined training, however, produced no additional effects on these variables.

**Short-term performance during the maximal exercise tests** was increased by 11% during cycling and 13% during treadmill running after strength and endurance training (Table 3). This was probably not a result of a greater anaerobic glycolytic capacity, since blood lactate levels were not significantly altered during cycling (~13 mM) or during running (10–12 mM) (Table 3).

**Long-term endurance**. The prestrength and endurance phase testing, which was performed over a minimum of 3-wk intervals, showed essentially the same average performances during cycling and running (Table 4). After strength and endurance training, cycling time to exhaustion was increased by 20% (Table 4). The 10-km run performance means for all subjects were not computed because of strength-related injuries to two individuals who could not effectively complete this testing (cycling testing or short-term running were not compromised). Of the six remaining subjects who ran, average performance was not significantly altered by the combination of training (Table 4).

**DISCUSSION**

Strength increases were not accompanied by any overall changes in muscle girth or fiber area. There are data supporting both a nervous and a muscular system factor in the adaptation to heavy-resistance exercise (cf. 21). Thus the accumulation of strength may reflect learning specific activation and motor unit recruitment patterns rather than significant intramuscular biochemical alterations, although the possibility of an increased contractile protein per cross-sectional area cannot be ruled out.

Although it is known that training for strength and endurance are not compatible when optimal levels of strength are the goal (6, 14), much less is known about the role of simultaneously training for strength and endurance-related performance. Several factors provided the background for undertaking this investigation. 1) When previously untrained individuals undergo strength training, there is little change in aerobic power, an observation consistent with almost all
**STRENGTH AND ENDURANCE TRAINING EFFECTS ON ENDURANCE**

![Graph showing strength changes after strength-training addition to endurance training. All values are significantly higher ($P < 0.05$) after strength and endurance training.](image)

**FIG. 1.** Strength changes after strength-training addition to endurance training. All values are significantly higher ($P < 0.05$) after strength and endurance training.

**TABLE 2.** Total body and skeletal muscle effects after strength-training addition to endurance training

<table>
<thead>
<tr>
<th>Training State</th>
<th>Thigh Girth, cm</th>
<th>Skin Folds, cm</th>
<th>%Body Fat</th>
<th>%Slow Twitch*</th>
<th>Fiber Area, μm²</th>
<th>VO₂max, ml·kg⁻¹·min⁻¹</th>
<th>Blood Lactate, mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endurance training</td>
<td>52.7±0.8</td>
<td>69.3±8.2</td>
<td>13.2±1.7</td>
<td>50±11</td>
<td>6058±85</td>
<td>54.4±1.8</td>
<td>362±10</td>
</tr>
<tr>
<td>After strength and</td>
<td>53.3±1.0</td>
<td>63.3±6.8</td>
<td>13.0±1.8</td>
<td>44±5</td>
<td>5935±590</td>
<td>54.8±1.7</td>
<td>403±25*</td>
</tr>
<tr>
<td>endurance training</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SE; $n = 8$ observations for total body measurements and $7$ observations for citrate synthase activity. *Means from 3 subjects.

**TABLE 3.** VO₂max, short-term endurance, and blood lactate responses to maximal exercise after strength-training addition to endurance training

<table>
<thead>
<tr>
<th>Training State</th>
<th>VO₂max, ml·kg⁻¹·min⁻¹</th>
<th>Short-Term Endurance, s</th>
<th>Blood Lactate, mM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycling</td>
<td>3.86±0.21</td>
<td>54.4±1.8</td>
<td>12.8±0.7</td>
</tr>
<tr>
<td>Endurance training</td>
<td>3.92±0.19</td>
<td>54.8±1.7</td>
<td>403±25*</td>
</tr>
<tr>
<td>After strength and</td>
<td>4.27±0.27</td>
<td>60.2±2.2</td>
<td>9.9±0.6</td>
</tr>
<tr>
<td>endurance training</td>
<td>4.29±0.27</td>
<td>60.0±2.0</td>
<td>407±21*</td>
</tr>
</tbody>
</table>

Values are means ± SE. VO₂max, maximal O₂ uptake. *Significantly different from endurance training ($P < 0.05$).

strength-training studies (1, 9, 14, 17, 18, 22, 28). However, it was observed that the capacity to perform high-intensity cycling or running to exhaustion can be improved after a program specifically strengthening the lower-limb musculature (17). These results suggested that the development of strength might be compatible with improving endurance in individuals already well trained in cycling or running. 2) Strength training by itself is known to produce muscular enlargement and increase body mass (7, 20, 26, 27). In particular, the strength program previously employed in our laboratory to strengthen the lower-limb muscles increased thigh girth by several centimeters as well as strength by 40–50% (16). Thus the potential contribution of the strengthened muscle mass could be counterbalanced by the increased mass itself. This factor would be deleterious to endurance, particularly during long term exercise when body mass represents a significant negative factor. 3) Competitive endurance athletes are known to incorporate, at various stages of training, some types of strength exercise into their regimen. Yet knowledge of the benefits or hazards of this supplementation to endurance training is completely lacking.

The present results demonstrate a complete absence of any negative physiological effects of adding strength training to a regular program of endurance exercise in well-trained subjects. In fact, the performance results generally show a positive effect on short-term endurance and on long term endurance to some extent. Since the strength training program did not induce any increase in total body mass, thigh girth, or fiber area, the potential negative influences on performance did not represent limiting factors to the results.
Short-term endurance was increased approximately equally (11–13%) during cycling and treadmill running after the strength and endurance phase of training. Strength-training programs, particularly those encompassing similar durations (2–3 mo) to that currently used, have been reported to increase the high-energy phosphate (creatine phosphate, ATP) and glycogen content at rest, the enzymatic capacity to rapidly resynthesize ATP, and the fast-twitch to slow-twitch fiber area ratio (7, 20, 27). These adaptations are geared to provide energy quickly, and may play a significant role in explaining part of the short-term performance increases. However, the possibility that these adaptations are compromised when both types of training are performed simultaneously is subject for future study.

Other factors, besides those accountable uniquely to the strength training, could have potentially influenced the increase in long-term cycling endurance. Although it was determined, based on performance and the increase in long-term cycling endurance. Although it was determined, based on performance and $V_{O_2\text{max}}$, that the subjects were at a “steady-state” level for 6–8 wk before beginning the strength phase, it was possible that further adaptations (i.e., muscle respiratory capacity) to the endurance training could have occurred during the steady-state phase. For example, Henriksson and Reitman (13) demonstrated a dissociation between $V_{O_2\text{max}}$ and muscle respiratory capacity, since they observed a further increase in the activities of the citrate cycle enzyme, succinate dehydrogenase, despite a plateauing of $V_{O_2\text{max}}$. Presently, the fact that the subjects were, in some cases, more familiarized with running than cycling, also suggested a greater potential for improvement.

Nonetheless, the lack of change after strength and endurance training in the activities of citrate synthase, another mitochondrial marker of the citrate cycle, argues against the concept that further metabolic adaptations had occurred with the continued endurance training. Furthermore, the half-lives of a number of mitochondrial proteins in skeletal muscle have been shown to be on the order of 1-wk (4). In response to a constant training stimulus, the half-time of the increase in $V_{O_2\text{max}}$ is ~10 days (15). These results, when taken cumulatively, support the long-term, pre-strength, and endurance performance profiles that the subjects were in steady state with regard to certain biochemical and physiological parameters.

At this time, a more likely explanation for the improved long-term cycling performance could be related to the strength training effects on fiber type recruitment during exercise. It has been reported that during sub-maximal continuous exercise on the cycle ergometer (85% $V_{O_2\text{max}}$, 60 rpm), the peak tension that can be developed with each pedal thrust amounts to 50–60% of the maximal force, which can be exerted on the pedals (2). This implies an asynchronous activation of motor units with a significant recruitment of fast-twitch fibers (11). In this study, strength training increased maximal force in the lower limbs by 30%. On the assumption that a proportional increase occurred in the maximal force that may be exerted on the pedals, the peak tension developed with each pedal thrust would decrease from 50 to 60% of the maximal force before strength training to 35–45% after strength training. These observations suggest an increased participation by slow-twitch fibers and a reduced rate of fast-twitch fiber recruitment with each pedal thrust, resulting in an accompanying decrease in ATP consumption per unit of contractile force (10) by the fast-twitch fibers and a probable glycogen-sparing effect in this fiber type (11). By postponing the contribution of fast-twitch muscle recruitment, fatigue may be delayed and time to exhaustion improved.

Although the 10-km run results remained somewhat inconclusive, in part due to injuries, several observations suggest that the weight-training effects on fiber-type recruitment would be markedly less significant during submaximal running exercise. During running at velocities between 3.62 m/s (10 km in 46 min) and 4.5 m/s (10 km in 37 min), the peak vertical force is ~2.4–3.0 body wt (total force/subject’s body weight) (cf. 6). These values represent ~40–50% of the peak vertical force developed during sprint running, which, in turn, represents ~45% of the peak force developed during a maximal vertical jump (23). Based on these data, estimates of peak vertical force, while running before strength and endurance training (10 km in ~42 min), would be ~20% of the maximal peak force exerted during the vertical jump. This would involve a low, even negligible recruitment of fast-twitch fibers during each step (11). In this context, the increase in force after strength training might have little effect on the rate of fast-twitch fiber recruitment, and consequently, on performance during the submaximal run.

In addition, this last possibility could explain why short-term endurance was improved after strength training during treadmill running. The increasing speed and treadmill incline during this test solicits a high rate of fast-twitch fiber recruitment. In this case, the effects of strength training would decrease the rate of fast-twitch fiber recruitment for the same velocity and consequently
could improve performance.

In conclusion, these results provide an initial basis for employing strength training to supplement certain types of endurance performance in individuals already conditioned for these activities. However, based on our results, the potential for injury may also increase with both types of training.

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