The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists

Abstract To investigate the effects of replacing a portion of endurance training by strength training on exercise performance, 14 competitive cyclists were divided into an experimental (E; n = 6) and a control (C; n = 8) group. Both groups received a training program of 9 weeks. The total training volume for both groups was the same [E: 8.8 (1.1) h/week; C: 8.9 (1.7) h/week], but 37% of training for E consisted of explosive-type strength training, whilst C received endurance training only. Simulated time trial performance (TT), short-term performance (STP), maximal workload ($W_{max}$) and gross (GE) and delta efficiency (DE) were measured before, after 4 weeks and at the end of the training program (9 weeks). No significant group-by-training effects for the markers of endurance performance (TT and $W_{max}$) were found after 9 weeks, although after 4 weeks, these markers had only increased ($P < 0.05$) in E. STP decreased ($P < 0.05$) in C, whereas no changes were observed in E. For DE, a significant group-by-training interaction ($P < 0.05$) was found, and for GE the group-by-training interaction was not significant. It is concluded that replacing a portion of endurance training by explosive strength training prevents a decrease in STP without compromising gains in endurance performance of trained cyclists.

Keywords Cycling · Resistance training · Endurance · Time trial

Introduction

Training is one of the most important modifiers of cycling performance (Jeukendrup and Martin 2000). The training volume of competitive road cyclists is often very large, and may amount up to 27,000–39,000 km/year (Jeukendrup et al. 2000). Recently, cross-training and incorporation of strength training (ST) has received considerable attention (Bishop et al. 1999; Marcink et al. 1991; Paavolainen et al. 1999). The results of investigations into the effect of ST on endurance performance (i.e. cycling performance) are somewhat contradictory. Some authors (Hickson et al. 1988) report a significant increase in performance, whilst others have found no effect (Bishop et al. 1999). On the one hand it can be argued that the authors who did find an effect used a high-volume (more than 30 sets/week) ST regime that was added to the normal training (Hickson et al. 1988; i.e. the effects were related to the training volume rather than to the ST per se). On the other hand it can be argued that in the study by Bishop et al. (1999) no effect was found because they employed a “slow” maximal strength-type training that could have contributed to the inability of their resistance training program to improve “high-speed” cycle endurance performance. Several authors have reported the velocity specificity of ST (Behm and Sale 1993; Bell and Wenger 1992; Kraemer et al. 1998; Sale and MacDougal 1981); some state that in particular the intention to make a high-speed movement plays a key role in velocity-specific training effects (Behm and Sale 1993). More to the point, data on the effect of specific (i.e. high speed) ST on the performance of cyclists, measured by reproducible testing methods, is still lacking.

Therefore, the aim of this study was to examine the effects of replacing a portion of endurance training with a program of explosive-type ST on endurance performance (measured by a simulated time trial, TT) and the short-term performance (STP) of competitive cyclists.
Methods

Subjects

Sixteen trained male competitive cyclists volunteered to participate in this study. During the competition season, subjects trained for at least 10 h/week [mean (SD) 13 (3) h/week]. They had been training at this level for at least 2 years [mean 6 (6) years]. All subjects were familiar with ergometer testing (to reduce the possibility of learning effects) and none of the subjects had been engaged in ST before. After being fully informed of the risks associated with participation, each subject gave his written consent to participate. The subjects’ physical characteristics are presented in Table 1.

General design

The subjects were assigned to either an experimental (E; n = 8) or a control group (C; n = 8). The groups were matched for mean training time during the 2 weeks preceding the start of the study. During the study period, two E subjects were excluded due to illness. The experimental training period lasted for 9 weeks and was executed before the start of the competition season. The E group received training that consisted of ST and endurance training, whereas the training for the C group consisted entirely of endurance training. Measurements were performed before the training period, after 4 weeks and at the end of the training period.

Training

The mean training time during the 2 weeks prior to the start of the investigation was 5.0 (2.7) h/week and 6.9 (2.6) h/week for the E and C group, respectively. This difference was not significant (P < 0.05). Training volumes during the experimental period were 8.8 (1.1) h/week (E) and 8.9 (1.7) h/week (C). For the E group, 37% of the total training volume consisted of ST, whilst training of the C group consisted entirely of endurance training.

For both groups, endurance training was divided into zones of different intensities using heart rate at ventilatory threshold (THvent). THvent was determined using an incremental ergometer test (see measurements). Training intensity was categorised into three zones, D1, D2 and D3, at respectively 75–85%, 85–95% and 95–100% of heart rate at THvent. Endurance training consisted of the same portions D1, D2 and D3 in both E and C groups [91 (3)% D1, 4 (3)% D2, 5 (2)% D3 and 90 (2)% D1, 4 (1)% D2, 6 (1)% D3, respectively]. The training volumes of both groups are presented in Fig. 1. All endurance training hours were performed during normal road training, on the subject’s own racing bicycle. Training intensity was controlled using a Polar Vantage heart-rate monitor (Polar, Kempele, Finland) and heart rate was recorded during all sessions. ST consisted of high-repetition, low-weight, explosive-type ST. For all exercises, 30 repetitions were made. Subjects were encouraged to perform the repetitions as explosively as possible. Weight was set at a level so that subjects could keep their speed of movement during the first 20 repetitions, and lost some power during the last 10. If subjects could finish the exercise with a constant pace, weight was increased and vice versa. Each ST session consisted of 4 series (i.e. 30 repetitions) of squats, 4 series of leg press and 4 series of step up (single legged). Furthermore, ST consisted of two sets of leg pull and some abdominal exercises to ensure upper body stability. A standard ST session started with a 10-min warm-up on a stationary bicycle, at 75% of maximal heart rate. Thereafter, two series of squats, two series of leg press, two series of leg pull and two series of step-up were performed. These series were repeated after 10 min of cycling at 75% maximal heart rate. The ST was concluded with 10 min cycling at 75% of maximal heart rate.

Measurements

Before the training period, after 4 weeks and after 9 weeks of training, the subjects performed three exercise tests. First, an incremental ergometer test (IE) was used to determine gross (GE) and delta efficiency (DE), THvent and maximal workload (Wmax). Briefly, IE consisted of a workload protocol which, after a 10-min warm-up at 1.5 W/kg, increased every 2.5 min by 0.167 W/kg until the subjects could not keep their pedalling rate up to the required cadence of 80 rpm. Second (on a separate day), STP was measured during a 30-s ergometer test at a fixed cadence of 60 rpm. Finally (on the same day as the measurement of STP), the subjects’ power output during a simulated TT was determined. All tests were performed on an electronically braked ergometer (IE and TT: Lode, Excalibur Sport, Groningen, The Netherlands; STP: Schoberer, SRM Hochleistungs Ergometer, Julich, Germany), which was equipped with the subjects’ own pedals and adjusted according to measurements of the subject’s own racing bike: saddle height, distance between the handle bars and the saddle, distance between the saddle and the vertical of the bottom bracket. Subjects were not allowed to perform heavy exercise on a testing day or the day before the first testing day. Furthermore, they were not allowed to eat in the hour preceding a test or to consume coffee or other products containing caffeine on a testing day. “Before” and “after” measurements were performed at the same time of the day to avoid

![Fig. 1 Relative training volumes of the different training modes in the experimental and control groups](image-url)

**Table 1** Characteristics of the subjects in the experimental (E) and control (C) groups. The data are presented as the mean (SD). (LBM Lean body mass)

<table>
<thead>
<tr>
<th>Variable</th>
<th>E group (n = 6)</th>
<th>C group (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>24 (8)</td>
<td>29 (12)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>182 (7)</td>
<td>186 (8)</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>89.1 (11.8)</td>
<td>77.7 (5.5)</td>
</tr>
<tr>
<td>LBM (kg)</td>
<td>61.1 (8.4)</td>
<td>67.5 (5.0)</td>
</tr>
<tr>
<td>Training 2 weeks prior to research (h/week)</td>
<td>5.0 (2.7)</td>
<td>6.9 (2.6)</td>
</tr>
<tr>
<td>Training during competition season (h/week)</td>
<td>12 (2)</td>
<td>13 (3)</td>
</tr>
<tr>
<td>Training experience (years)</td>
<td>5 (4)</td>
<td>8 (7)</td>
</tr>
</tbody>
</table>
circadian variance. During IE and TT, heart rate was measured using a Polar Vantage heart rate monitor (Polar). During IE, oxygen uptake (\(\dot{V}O_2\)), ventilation rate (\(V_e\)) and respiratory exchange ratio (\(R\)) were measured continuously using a Metalyzer (Cortex, Germany). Finally, anthropometric measurements of the subjects were taken. Percentage body fat was estimated from the sum of four skinfolds (triceps brachii, biceps brachii, subcapularis and suprailium).

**Ventilatory threshold**

\(T_\text{vent}\) was measured during IE. \(T_\text{vent}\) was established at the highest workload increment at which there was a linear increase of \(\dot{V}e\) against the workload. Two investigators determined this workload independently, and in the case where the two investigators did not agree about the \(T_\text{vent}\), a third investigator was consulted.

**Maximal workload**

\(W_{\text{max}}\) during IE was defined as the highest workload at which the subjects could keep the pedalling rate up to the required 80 rpm. If they could not complete a workload increment, \(W_{\text{max}}\) was calculated with linear extrapolation, using the following formula:

\[
W_{\text{max}} = W_{\text{last}} + (t/150) \times (0.167 \times m)
\]

(1)

where \(W_{\text{last}}\) is the workload of the last completed stage, \(t\) is the time in seconds in the final stage, and \(m\) represents the subject’s body mass in kilograms.

**Delta and gross efficiency**

GE was calculated as the ratio of work accomplished per minute to energy expended per minute. Energy expenditure per minute was calculated from \(\dot{V}O_2\) and \(R\), using the tables of Lusk (1928). GE was then calculated as the average GE of the increments that elicited 50–70% peak \(\dot{V}O_2\) (\(\dot{V}O_2^{\text{peak}}\), Coyle et al. 1992), which was measured during the pre-training IE. These increments were also used for the calculation of GE and DE after 4 weeks of training, and post-training, to facilitate statistical comparisons. DE is defined as the ratio of the change in work accomplished per minute to the change in energy expended per minute. DE was calculated for each individual from linear regression (\(y = mx + b\)) of the relationship between energy expended per minute versus work accomplished per minute, using data points from 50–70% of \(\dot{V}O_2^{\text{peak}}\). DE was then calculated from the slope of the relationship and was equal to the reciprocal of \(m\) (i.e. 1/m; Coyle et al. 1992).

**Short-term performance**

STP was measured by calculating the mean power output during a 30-s ergometer test at a fixed pedal rate of 60 rpm. A 10-min warm up at 150 W preceded the test and each subject performed a learning trial. During the actual test subjects were encouraged vigorously. Torque was measured at a frequency of 200 Hz, and from that, mean power during the test was calculated.

**Time trial performance**

The TT was performed on an ergometer that was switched from a pedalling-independent, to a pedalling-dependent (linear) mode. In the linear mode, the work rate will increase with increasing cadence according to the following formula:

\[
\dot{W} = L \times (\text{rpm})^2
\]

(2)

where \(\dot{W}\) is the work rate, rpm is the cadence and \(L\) is a constant factor. The subjects performed a 1-h TT according to Jeukendrup et al. (1996). They were asked to perform a certain amount of work (equal to about 1 h of cycling) as fast as possible. The work they had to complete was based on \(W_{\text{max}}\), which was measured during the IE, according to the formula:

\[
\text{Target amount of work (J)} = 0.80 \times W_{\text{max}} \times 3600
\]

(3)

with the assumption that the subjects could cycle for about 1 h at a power output of 80% \(W_{\text{max}}\). The ergometer (in linear mode) was then set such that a pedal rate of 90 rpm would result in a power output of 80% \(W_{\text{max}}\). In other words, when subjects cycled at 90 rpm (a preferred cadence for many subjects), they would complete the TT in 1 h. The subject received feedback about the amount of work that had already been performed and elapsed time, but received no information about his workload, cadence and heart rate. The time needed to complete the total amount of work was recorded and mean power output was calculated from that.

**Statistics**

Means and SDs were calculated by standard methods and Pearson correlation coefficients were used to determine the relationships among the variables. The significance of differences between the changes within the E group and changes within the C group (group-by-training interaction), was tested by a General Linear Model for repeated measures. If a significant F-value was observed, Student’s t-test was used to identify differences within groups. Data are presented in the form mean (SD).

**Results**

During the training period the power output achieved during the simulated TT increased in the E group [before 257.5 (34.6) W; after 285.2 (30.1) W; 11.2 (7.9)%] and the C group [before 290.2 (33.6) W; after 312.4 (32.5) W; 7.9 (5.9)%]. There was no significant group-by-training effect for TT because both increases were significant \((P < 0.01)\), although after 4 weeks of training the increase in the E group was significant \((P < 0.05)\), whilst the C group did not show a significant change in TT (Fig. 2). Increases in \(W_{\text{max}}\) were 7.1 (4.7)% (E) and 4.8 (3.9)% (C) (Table 2). Although the increase was
somewhat higher for the E group than for the C group, there was no group-by-training interaction for $W_{\text{max}}$. Again, after 4 weeks of training, the increase in $W_{\text{max}}$ was only significant in the E group (Fig. 3).

A significant group-by-training interaction was found for STP ($P < 0.05$); this was caused by a decrease ($P < 0.05$) in the C group (Table 3, Fig. 4). DE showed the same results: the group-by-training interaction was significant ($P < 0.05$) (Fig. 5), although both the increase (E) and decrease (C) were not significant (Table 3). The increase in GE tended to be larger in the E group than in the C group (Table 3), but the group-by-training interaction was not significant. Lean body mass (LBM) increased in the E group [from 61.1 (8.4) kg to 62.8 (7.6) kg] and the C group [from 67.5 (5.0) kg to 68.5 (5.0) kg], but the group-by-training interaction effect on LBM was not significant.

**Table 2** Maximal power output ($W_{\text{max}}$) in the incremental ergometer test and average power in the simulated time trial, before and after 4 weeks and 9 weeks of training. (NS Not significant)

<table>
<thead>
<tr>
<th>Variable</th>
<th>E group ($n = 6$)</th>
<th>C group ($n = 8$)</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After 4 weeks</td>
<td>After 9 weeks</td>
</tr>
<tr>
<td>$W_{\text{max}}$ (W)</td>
<td>314 (35)</td>
<td>327 (29)*</td>
<td>335 (31)**</td>
</tr>
<tr>
<td>Time trial (W)</td>
<td>257.5 (34.6)</td>
<td>268.4 (25.1)*</td>
<td>285.2 (30.1)**</td>
</tr>
</tbody>
</table>

*Significantly different from before ($P < 0.05$); **significantly different from before ($P < 0.01$)

![Fig. 3](image3.png) Average ($\pm$SD) maximal power ($W_{\text{max}}$), relative to pre-training values, in an incremental ergometer test in the E and C groups. *$P < 0.05$; **$P < 0.01$

![Fig. 4](image4.png) Average ($\pm$SD) short-term performance (STP), relative to pre-training values, in an ergometer test performed at a pedal cadence of 60 rpm in the E and C groups. *$P < 0.05$

![Fig. 5](image5.png) Mean delta efficiency ($\pm$SD) in the E and C groups

**Table 3** Short-term performance (STP), gross efficiency (GE) and delta efficiency (DE) during the incremental ergometer test, before and after 4 weeks and 9 weeks of training

<table>
<thead>
<tr>
<th>Variable</th>
<th>Experimental group ($n = 6$)</th>
<th>Control group ($n = 8$)</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After 4 weeks</td>
<td>After 9 weeks</td>
</tr>
<tr>
<td>STP (W)</td>
<td>665.8 (50.5)</td>
<td>695.1 (85.3)</td>
<td>693.7 (98.9)</td>
</tr>
<tr>
<td>GE (%)</td>
<td>21.17 (0.78)</td>
<td>21.92 (0.32)</td>
<td>22.29 (1.13)</td>
</tr>
<tr>
<td>DE (%)</td>
<td>24.63 (1.41)</td>
<td>26.95 (4.71)</td>
<td>26.22 (4.37)</td>
</tr>
</tbody>
</table>

*Significantly different from before ($P < 0.05$)
Correlation analysis showed that the improvement in TT correlated significantly \((P < 0.01)\) with the increase in \(W_{\text{max}}\) \((r = 0.61)\). Changes in DE and GE were not associated with the improvements in TT and \(W_{\text{max}}\), except for DE, which correlated significantly \((P < 0.05)\) with \(W_{\text{max}}\) \((r = 0.41)\).

**Discussion**

Previous investigations (Hickson et al. 1988; Marcinik et al. 1991) have reported a potential for ST to enhance endurance performance. However, the ST regime in these investigations was added to the existing training schedule, and thus any changes in performance could be attributed to an increased total volume of training. Therefore, the purpose of this study was not to investigate the effects of a ST regime added to an endurance-training program, but rather a ST regime that replaced a portion of the endurance training.

It was found that a ST regime of 9 weeks that replaced a portion of the endurance training had no effect on TT performance compared to endurance training with a similar total volume. However, whereas STP decreased after endurance training, this decrease was prevented by ST. Another important finding, especially from a practical point of view, is that after 4 weeks, the markers of endurance performance increased \((P < 0.05)\) only in the E group. These results suggest that adaptations in endurance performance occur faster after combined strength and endurance training than after endurance training alone.

It has been argued that by increasing the maximal force, the peak tension developed by each pedal thrust (in the case of cycling) would decrease to a lower percentage of maximal force, allowing an increased participation of slow-twitch fibres and a reduced rate of fast-twitch fibre recruitment (Hickson et al. 1988). We hypothesised that this could then result in a higher efficiency, because cycling efficiency has been related to the percentage of slow-twitch fibres in the active muscle (Coyle et al. 1992; Horowitz et al. 1994), assuming that a high percentage of slow-twitch fibres in the active muscle can be equated with a high rate of slow-twitch fibres that contribute to the movement. Indeed for DE, there was a group-by-training interaction effect, caused by an increase in the E group \([\text{from 24.63 (1.41\%) to 26.22 (4.37\%)\]}\) and a decrease in the C group \([\text{from 24.99 (1.32\%) to 24.13 (2.28\%)\]}\). GE also tended to increase more in the E group, although for this variable no significant group-by-training interaction could be established. Therefore, this hypothesis remains inconclusive.

It has been reported that ST can increase STP (Hickson et al. 1988; Paavolainen et al. 1999) due to the increase in high-energy phosphate and glycogen content at rest, the enzymatic capacity to rapidly resynthesise ATP, and the fast-twitch:slow-twitch fibre area ratio (Hickson et al. 1988). In the present study, the ST program was designed primarily to induce an additional effect on endurance performance, and therefore consisted of a high-repetition, low-resistance schema that is likely to produce only neural adaptations (Kraemer et al. 1998), and was performed simultaneously with an endurance training program that consisted solely of low to moderate training intensity (up to \(T_{\text{vent}}\)). This is in contrast with the aforementioned investigations in which a high-resistance, low-repetition program (Hickson et al. 1988), or a combined ST and partially high-intensity (above lactate threshold, circuit-training) training program (Paavolainen et al. 1999) was used. This may explain the insignificant increase in STP we measured in the E group. However, ST did cause a significant group-by-training effect, because the STP in the C group decreased \((P < 0.05)\). Although in this group STP decreased, the total training volume increased from 6.9 (2.6) h/week before the start of the investigation to 8.9 (1.7) h/week during the experimental period. It has been reported that endurance training can reduce maximal strength (Widrick et al. 1996), but a decreased STP (anaerobic-like) after endurance training has, to our knowledge, not been established before. Obviously, the testing procedure used in this investigation (a 30-s ergometer test in which subjects had to perform as much work as possible at a fixed cadence of 60 rpm) is rather unique. We felt that this test had to consist of: (1) a “closed end”, which results in a low coefficient of variation (Jeukendrup et al. 1996), and (2) a very short duration, but long enough to cause a change of fibre recruitment from fast to slow (Jacobs et al. 1981).

The ST regime was designed to enhance cycling performance. All movements were explosive-type, in accordance with investigations that report velocity specificity of ST (Behm and Sale 1993; Bell and Wenger 1992; Kraemer et al. 1998; Sale and Macdougall 1981) and the finding that the intention to make a high-speed movement plays a key role in velocity-specific training effects (Behm and Sale 1993). Furthermore, in agreement with the findings of Morrissey et al. (1995) that there is only a training effect at the joint angles that are trained, the ST was executed at a knee angle not smaller than 90°, because peak force is exerted when the pedal is at an angle of 90° (straightforward) with an approximate knee angle of 90° (Coyle et al. 1991). All eccentric movements were performed at a slow and constant movement velocity, because power in cycling is produced by concentric contraction, and because there is evidence that after eccentric contractions replenishment of muscle glycogen is impaired (Costill et al. 1990) and muscle hypertrophy is accelerated (Sale and Macdougall 1981). This factor would be deleterious to endurance performance, particularly during long-term exercise when body mass represents a significant factor. Indeed, in the present investigation there was no significant group-by-training effect for LBM, indicating that replacing a portion of endurance training by our ST program does not accelerate muscle hypertrophy. Finally, during all ST exercises, the number of repetitions was high, to ensure a high rate of slow-twitch fibre recruitment, as reported by Jacobs et al. (1981).
In conclusion, for competitive road cyclists, replacing a portion of endurance training by explosive ST prevents a decrease in STP without compromising gains in endurance performance.

The practical implication of this finding is that for road cyclists it is profitable to dedicate a portion of the total training time to ST. The significance of this finding should be regarded in light of the day-to-day training circumstances of a road cyclist, which can be unfit for training on the road (e.g. during poor weather conditions). Therefore, alternative training methods are needed when conditions for road training are poor. The current results indicate that replacing endurance training by ST is more than a fall back arrangement when conditions are unsuitable for road training. Furthermore, the present investigation indicates that replacing a part of endurance training by ST is especially recommended when a fast improvement in endurance performance (for example an improvement of performance in a 1-h TT, within 4 weeks) is required.

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References

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