

Strength training reduces freely chosen pedal rate during submaximal cycling

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Abstract The freely chosen pedal rate is relatively high and energetically inefficient during submaximal cycling, which is a paradox since the rate of energy expenditure is considered important for voluntary motor behavior in other cyclical activities as, e.g., running. For example, it has been suggested that subjects pedal fast to reduce the perception of force. In this study, we investigated the hypothesis that strength training would cause subjects to pedal at a slower rate during low to moderate submaximal cycling. Fourteen healthy subjects performed supervised heavy (2–12 RM) strength training 4 days/week for 12 weeks, including 2 days/week with leg-extensor and knee-flexor exercises. Seven healthy subjects formed the control group. The training group increased strength (one repetition maximum, 1 RM) in both squat [20%(3), mean (SEM)] and leg curl [12%(1)] exercises from the beginning to the end of the study period ($p < 0.01$). At the same time, freely chosen pedal rate was reduced by 8 (2) and 10 (2) rpm, respectively, during cycling at 37 and 57% of maximal power output (W_{\max}) ($p < 0.01$). In addition, rate of energy expenditure is 3% (2) lower at 37% of W_{\max} ($p < 0.05$) and tended to be lower at 57% W_{\max} ($p = 0.07$) at the end of the study. Values for strength, freely chosen pedal rate, and rate of energy expenditure, were unchanged for the control group from the beginning to the end of the study. In conclusion, strength training caused subjects to choose a ~ 9 rpm lower pedal rate during submaximal cycling. This was accompanied by a $\sim 3\%$ lower rate of energy expenditure.

Keywords Central pattern generators · Cycling economy · Motor behavior · Preferred pedaling cadence · Resistance training

Introduction

During submaximal cycling, at an intensity up to approximately 70% of the maximal rate of oxygen uptake ($VO_{2\max}$), the freely chosen pedal rate (e.g., 70–90 rpm) is less energetically efficient (i.e., results in high VO_2 and rate of energy expenditure) compared with lower pedal rates (e.g., 50–60 rpm) (Nielsen et al. 2004). This phenomenon has been observed in children (Klausen et al. 1985), recreationally active adults (Hansen et al. 2002), trained runners (Marsh and Martin 1997), and trained cyclists (Foss and Hallén 2005; Hansen et al. 2006; Marsh and Martin 1997) and therefore appears as a general behavior particularly occurring within cycling. The phenomenon is a paradox since the rate of energy expenditure is considered important for voluntary motor behavior in cyclical activities like walking, running and pedaling (Sparrow and Newell 1998; Almåsbaek et al. 2000). In fact, during walking and running the preferred step rate is energetically optimal (Martin et al. 2000).

In addition, it has been suggested that the perception of force causes subjects to choose a high and inefficient pedal rate (Stegemann et al. 1968). This is consistent with the knowledge that the force in each pedal thrust decreases with increasing pedal rate as a consequence of the hyperbolic relationship between pedal rate and pedal force (Böning et al. 1984; Hansen et al. 2002; Löllgen et al. 1980; Takaishi et al. 1998). It has also, on basis of the muscle fibres' contractile and energetic properties, been suggested that subjects as a compromise choose a pedal rate that

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activate their muscle fibers at a velocity between the optimal velocity for energetic efficiency and the higher optimal velocity for maximal power production (Kohler and Boutilier 2005). Still, firm evidence of the various factors affecting the freely chosen pedal rate during cycling is sparse. Perhaps some combination of central effort sensation (reflecting energy expenditure, originating from the cardiopulmonary system, and including breathlessness as well as heartbeat intensity) and local effort sensation (reflecting muscle load and joint strain in the legs and originating from both mechano- and chemo-receptors) determines the choice of pedal rate during cycling since both sensations influence perceived exertion (Mihevic 1981).

In this study we investigated whether strength training would cause subjects to decrease their pedal rate during submaximal cycling, thereby reducing the rate of energy expenditure and load on the cardiopulmonary system, even as pedal force increases. Such a result would challenge the view that adaptation in the neuromuscular system optimizes only the practiced movement, and not other movements in which the neuromuscular elements are involved (Bawa 2002). It is well known that strength training increases maximal strength as a consequence of enlarged muscle cross sectional area and neural adaptations [for review see, Gabriel et al. (2006)]. What is less well understood is to what extent strength training affects voluntary motor behavior during submaximal exercise. The knowledge gleaned from the present study may expand the general understanding of human voluntary motor behavior in cyclical activities, such as cycling, that is a widespread type of transport, exercise and sport.

Thus, the purpose of the present study was to test the hypothesis that strength training would cause subjects to reduce the freely chosen pedal rate during low to moderate submaximal cycling, and that this would be accompanied by a lower rate of energy expenditure.

Methods

Subjects

A total of 29 subjects volunteered for the study, which was approved by the regional ethics committee. The subjects signed an informed consent form prior to participation, and were told that the purpose of the study was to investigate the effect of strength on energy expenditure during cycling. To reduce the risk of unduly influencing pedal rate, the subjects were blinded to the intent to examine the effect of strength training on freely chosen pedal rate. Although all subjects were able to ride a bicycle, the majority of them rarely cycled. This choice of subjects was made intentionally so that the subjects could be minimally affected by

cycling coaches' and cyclists' position on "right pedaling". None of the subjects altered their cycling habits during the study period. To minimize potential dropouts from the training group, all subjects must have had experience with strength training on a recreational basis. Still, before the study, none were involved in strength training regimens as intensive as in the present study. Twenty-one subjects formed the training group. Seven of these subjects dropped out of the study because of illness (unrelated to the training), personal reasons, or no reason given. The remaining 14 subjects from the training group (8 women and 6 men) completed the study. Eight subjects formed the control group. One of these subjects dropped out because of personal reasons while the remaining seven subjects from the control group (2 women and 5 men) completed the study. From the beginning of the study the gender distribution in the training and control group was similar. Unfortunately, more men dropped out from the training group. The subjects' physical characteristics at the beginning of the study are presented in Table 1.

Experimental design

All the subjects were familiarized with the maximal strength test while only subjects in the training group were familiarized with the training regimen. Maximal strength tests were performed at the beginning (week 0) and end (week 12) of the study. A maximal cycling test was performed at the beginning of the study while submaximal cycling tests were performed at the beginning and the end of the study. A minimum of 1 day separated leg strength training and tests.

Training

The subjects in the training group completed supervised heavy strength training, 4 days/week, for 12 weeks. The training was designed as a two-split program including 2 days/week with heavy and lighter training, respectively, for each muscle group. Leg exercises (2 days/week) consisted of squat, knee extension, sitting leg curl, standing calf raise, and two core exercises (sit-ups on an incline abdominal board and abdominal crunch in a machine). In addition, subjects performed 11 upper body exercises (2 days/week) as other outcomes of the strength training

Table 1 Subject characteristics at the beginning of the study

	Age (years)	Height (cm)	Body mass (kg)
Training ($n = 14$, 8 women)	26.4(1.3)	174.4(2.6)	73.2(5.3)
Control ($n = 7$, 2 women)	27.9(1.3)	178.1(3.5)	76.7(5.6)

were also investigated. The training was periodized, following a linear increase in resistance and a parallel decrease in repetitions per set. In the first 4 weeks, subjects lifted weights with which they could complete 8–12 repetitions before exhaustion in 3–4 sets (8–12 RM sets), in the next 4 weeks they trained with 5–10 RM sets, and in the last 4 weeks they trained with 2–8 RM sets (3–4 sets per exercise). Training adherence was 100%. If subjects missed a supervised workout, they completed a similar workout on another day, on their own.

The subjects in the control group were told to continue their usual daily activities throughout the study.

Testing

Maximal strength

The maximal weight that could be lifted in one repetition (1RM) was determined in squat and leg curl. The squat test (and training) was performed in a Smith-machine and the deepest position was set to the point where femur was in parallel with the floor. A rubber band was individually adjusted so that subjects gently touched the band with their buttocks in the deepest position. In the leg curl subjects were seated with fixed hips and the test started with full extension in the knee joint and ended at a knee angle of 90°. For warm up, the subjects performed a standardized protocol of 12, 10, 7, and 3 repetitions with weights corresponding to estimates of 40, 60, 75, and 85% of 1 RM. The first attempt was then performed with a weight corresponding to 95% of the expected 1 RM. After each successful attempt, the weight was increased by 2–5% until failure. Attempts were separated by 3-min rest periods.

Maximal cycling

Before the progressive cycling test, the subjects performed a self-imposed warm up on the electromagnetically braked cycle ergometer (Lode Excalibur Sport, Lode, Groningen, The Netherlands) that was used for all cycling tests. After a short rest, the test was initiated with 2 min cycling at a power output corresponding to 3 W kg⁻¹ (rounded down to the nearest 50 W) at freely chosen pedal rate. Thereafter, the power output was increased by 50 W every other min until exhaustion. Maximal power output (W_{\max} , y) was calculated in style with (Lucia et al. 2004) as $y = x + ((a/120 \text{ s})50 \text{ W})$, where x is the second to last commenced power output and a is seconds of cycling at the last commenced power output. VO_2 , carbon dioxide output (VCO_2), respiratory exchange ratio (RER), and expiratory pulmonary ventilation (V_E) were measured continuously with SensorMedics Vmax 29 (AKU MED A/S, Oslo, Norway). The gas analyzers were calibrated against certified gases of

known concentrations prior to each test, and the ventilation sensors were calibrated frequently with a 3-liter syringe. Maximal respiratory values were determined as the highest 30 s means. Maximal heart rate was measured with a Polar S610 heart rate monitor (Electro Oy, Kempele, Finland). Maximal blood lactate concentration ([La]) was measured 1 min after exhaustion using an YSI Model 1500 Sport (YSI, Inc., Yellow Springs, OH, USA).

Submaximal cycling at 60 rpm

For the submaximal cycling sessions, 37 and 57% of W_{\max} were calculated. Before the test, the subjects performed a 5-min warm up at 37% of W_{\max} using freely chosen pedal rate. The subjects then performed 5 min cycling at 37% of W_{\max} at 60 rpm. After a 1-min rest, they continued with 5 min cycling at 57% of W_{\max} at 60 rpm. VO_2 was measured for 30 s periods throughout the cycle bouts and the median of the last three measurements were selected for further analyses. Heart rate was noted in the last minute while RPE was rated using Borg's 6–20 scale at the end of the bouts (Borg 1970). Rate of energy expenditure, expressed in W, was calculated from gross VO_2 and their corresponding RER values using the tables by Lusk (1976). Delta efficiency was calculated as the difference in power output between bouts at the submaximal work loads divided by the corresponding difference in rate of energy expenditure. The reason for including standardized bouts at a preset pedal rate in the study was to control for the possibility that strength training, per se, could change the economy of cycling at a fixed pedal rate.

Submaximal cycling at freely chosen pedal rate

This test was performed on a subsequent day using the same protocol as that of submaximal cycling at 60 rpm, except that the pedal rate was freely chosen. The freely chosen pedal rate was noted in the end of each minute and an average of the last 2 min was calculated.

Statistics

The training and control group were compared using Student's two-tailed t -tests (characteristics at the beginning of the study, results from the maximal cycle ergometer test, delta efficiency, differences between pre- and post-measurements of maximal strength and freely chosen pedal rate) and with Student's one-tailed t -tests (differences between pre- and post-physiological measurements during cycling at freely chosen pedal rate). Pre- and post-measurements within the groups were compared using paired Student's two-tailed t -tests (maximal strength and freely chosen pedal rate) and with paired Student's one-tailed t -tests

(physiological measurements during submaximal cycling). The relationship between maximal strength and freely chosen pedal rate at the beginning of the study as well as the relationship between changes in these variables during the study were examined with the Pearson product-moment correlation coefficient test. Statistics were calculated in Excel 2003 (Microsoft Corporation, WA, USA). Data are presented as mean (SEM). $p < 0.05$ was considered statistically significant.

Results

$\text{VO}_{2\text{max}}$ and W_{max} at the beginning of the study were lower for the training group than the control group ($p < 0.05$, Table 2). This is likely due to the greater proportion of females in the training group (Table 1). Consequently, power output corresponding to 37 and 57% of W_{max} was also lower for the training group compared with the control group [94(5) and 145(8) W vs. 124(12) and 191(19) W, $p < 0.05$].

Relative exercise intensity during cycling at freely chosen pedal rate at 37 and 57% of W_{max} at the beginning [and end] of the study was 51%(1) [49%(1)] and 68%(1) [67%(1)] of $\text{VO}_{2\text{max}}$, respectively, for the training group. Corresponding values were 49%(1) [49%(1)] and 66%(2) [68%(2)] for the control group. The relative values of VO_2 during cycling at 60 rpm at 37 and 57% of W_{max} at the beginning of the study were 48%(1) and 66%(1) of $\text{VO}_{2\text{max}}$, respectively, for the training group. Corresponding values were 44%(1) and 63%(1) for the control group.

The training group increased 1 RM in both squat (20%(3), $p < 0.01$) and leg curl (12%(1), $p < 0.01$). In comparison, the control group showed similar strength at the beginning and the end of the study, and the differences between the pre- and post-values were significantly higher for the training group than the control group ($p < 0.01$, Fig. 1). The change in body mass during the study was larger for the training group than the control group ($p < 0.01$), as body mass increased 4%(1) for the training group ($p < 0.01$) while it remained unchanged for the control group.

Freely chosen pedal rate for the training group decreased during submaximal cycling at 37 and 57% of W_{max} by 8(2) and 10(2) rpm, respectively, from the beginning to the end

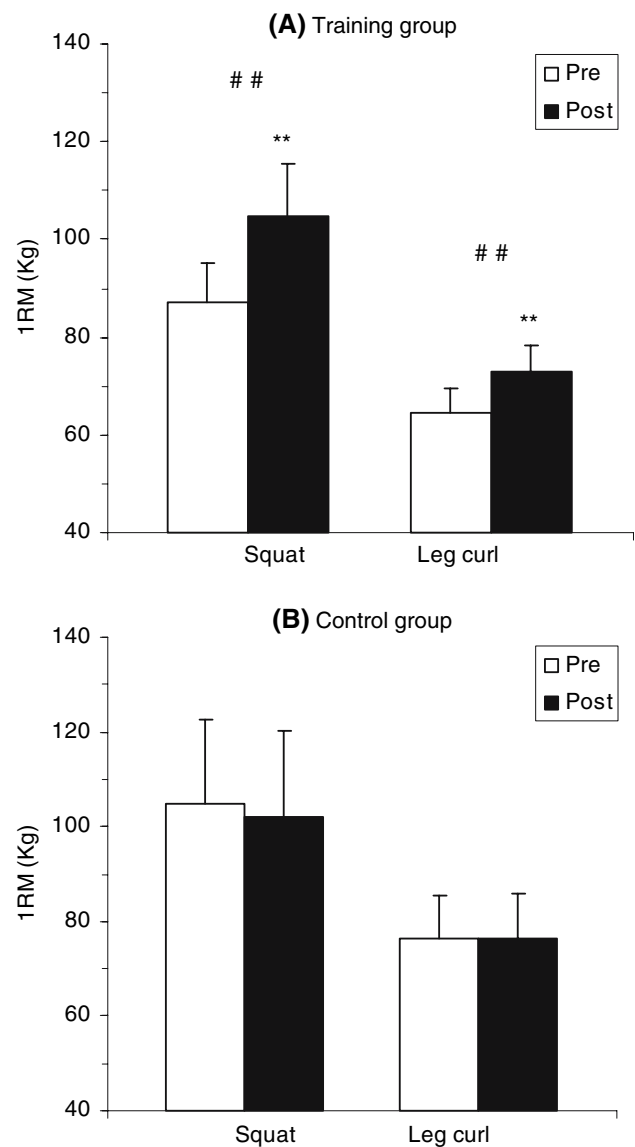


Fig. 1 Maximal strength for the training group (a) and control group (b), determined as one repetition maximum (1 RM) in squat and leg curl. Pre and post represents the beginning and the end of the study, respectively. **Different from pre, $p < 0.01$. ##The difference between pre- and post-measurements is different from the corresponding value in the control group, $p < 0.01$

of the study ($p < 0.01$). In comparison, the freely chosen pedal rate did not change for the control group (Fig. 2). The change in pedal rate at 57% of W_{max} during the study was larger for the training group than for the control group

Table 2 Results from the maximal cycle ergometer test at the beginning of the study

	W_{max} (W)	$\text{VO}_{2\text{max}}$ (ml min^{-1})	RER	V_E (l min^{-1})	Heart rate (beats min^{-1})	[La] (mM)
Training	254(14)	3371(211)	1.13(0.01)	130.9(10.5)	191(2)	9.1(0.5)
Control	335(34)*	4286(425)*	1.10(0.02)	157.2(18.5)	186(3)	8.3(0.8)

* Different from the training group, $p < 0.05$

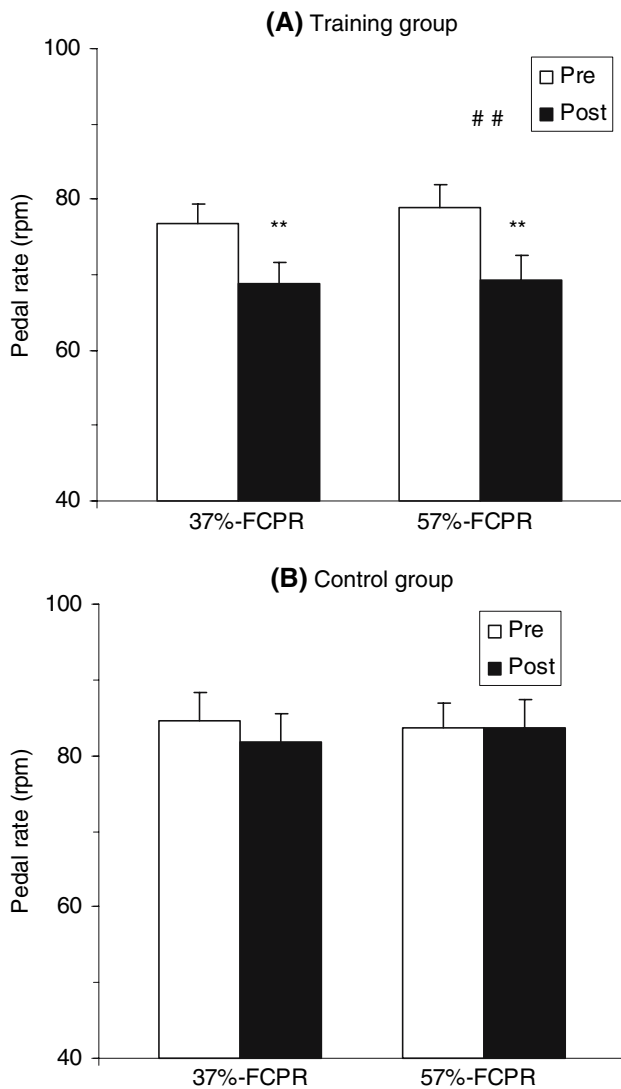


Fig. 2 Freely chosen pedal rate for the training group (a) and control group (b) during submaximal cycling at 37 and 57% of W_{\max} . **Different from pre, $p < 0.01$. ##The difference between pre- and post-measurements is different from the corresponding value in the control group, $p < 0.01$

($p < 0.01$). There was no significant correlation ($n = 21$) between any of the two maximal strength measurements and any of the two measurements of freely chosen pedal rate at the beginning of the study. In addition, there was no significant correlation ($n = 14$) between increases in maximal strength and corresponding changes in freely chosen pedal rate.

Within the training group, the lower freely chosen pedal rate during cycling at 37% of W_{\max} at the end of the study was accompanied by a 5%(2) lower heart rate ($p < 0.01$), 3%(2) lower VO_2 ($p < 0.05$), and 3%(2) lower rate of energy expenditure ($p < 0.05$). Similarly, heart rate was 4%(2) lower ($p < 0.01$) while VO_2 and rate of energy expenditure tended to be lower ($p = 0.11$ and $p = 0.07$,

respectively) during cycling at freely chosen pedal rate at 57% of W_{\max} at the end of the study. The control group showed no such differences. Some of the post- vs. pre-study differences in VO_2 and rate of energy expenditure during cycling at freely chosen pedal rate were significantly larger in the training group than in the control group (Fig. 3 and Table 3).

All the physiological measurements obtained during submaximal cycling at 60 rpm were similar at the beginning and the end of the study in both groups (Table 3). Thus, delta efficiency did not change, being 25.6%(0.8) and 25.6%(1.0) at the beginning and at the end of the study, respectively, for the training group. Corresponding values for the control group were 24.5%(1.0) and 24.8%(0.9). There was no significant difference between the groups.

Discussion

The present study confirmed the hypothesis that heavy strength training causes subjects to reduce their freely chosen pedal rate during submaximal cycling. This finding was accompanied by a reduced rate of energy expenditure.

The magnitude of the maximal strength increments was comparable to what has been seen previously in studies with similar subjects and training regimens (Fleck and Kraemer 2004). Larger improvements in strength are possible to attain although it may, e.g., require that the study subjects have less recent experience with strength training than the subjects in this study. In addition, the improvement in maximal strength (12% for leg curl and 20% for squat) corresponded with the increase in force in each pedal thrust that is known to follow from a 10 rpm reduction in pedal rate at power output levels like those used in this study [around 10–17% (Böning et al. 1984; Takaishi et al., 1998)]. However, we cannot conclude that there is a causal relationship between maximal leg strength per se and choice of pedal rate since maximal strength and freely chosen pedal rate were not correlated in this study, despite the large variation in both variables (e.g., 40–200 kg in squat and 55–97 rpm at 57% of W_{\max}). An absence of a relationship between maximal voluntary isometric knee extension torque and freely chosen pedal rate has been reported before (Hansen et al. 2002). In addition we found that improvement in maximal strength was not correlated to reduction in freely chosen pedal rate, which would support that strength per se does not determine pedal rate. However, if strength per se does not determine the choice of pedal rate, then other outcomes of the strength training should be considered as possible reasons for the significantly changed pedaling behavior.

Changes within the neuromuscular system may be involved. However, knowledge of the precise nature of the

Fig. 3 Oxygen uptake for the training group (a) and control group (b) during submaximal cycling at 37 and 57% of W_{max} at freely chosen pedal rate and 60 rpm. *Different from pre, $p < 0.05$. ##The difference between pre- and post-measurements is different from the corresponding value in the control group, $p < 0.01$

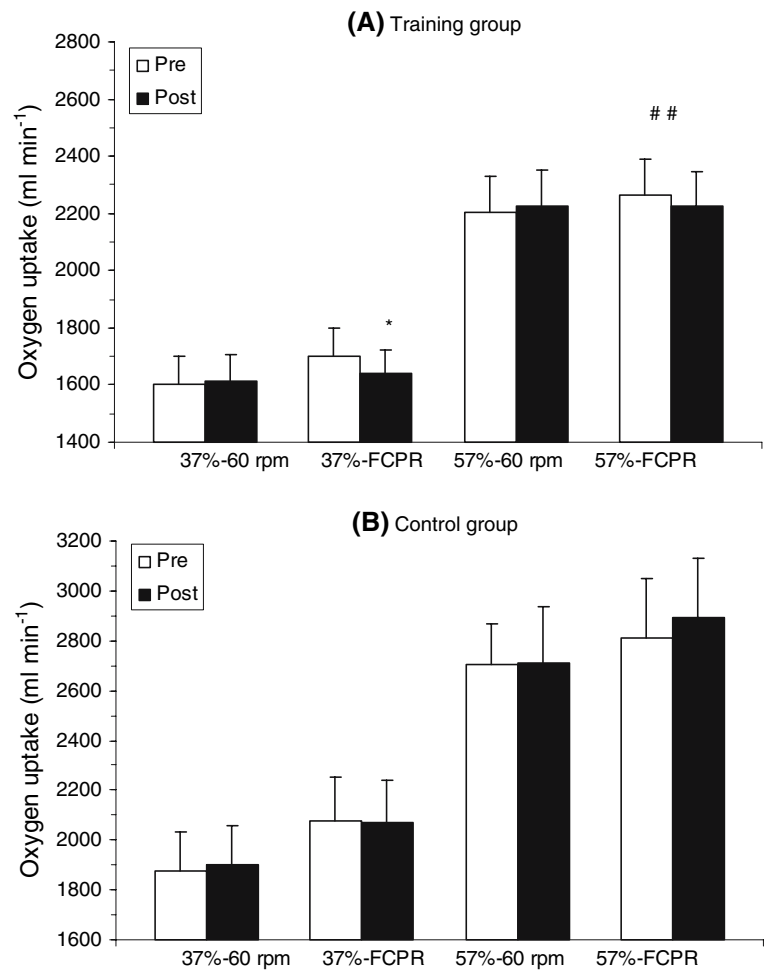


Table 3 Results from submaximal cycling at the beginning (pre) and the end (post) of the study

	37% of W_{max}				57% of W_{max}			
	Heart rate (beats min ⁻¹)	RER	REE (W)	RPE	Heart rate (beats min ⁻¹)	RER	REE (W)	RPE
Freely chosen pedal rate								
<i>Training</i>								
Pre	135(5)	0.89(0.01)	582(33)	10.9(0.4)	156(4)	0.94(0.01)	781(44)	14.1(0.2)
Post	127(3)**	0.89(0.01)	560(28)*	9.9(0.6)	149(3)**	0.92(0.01)	767(41)##	13.9(0.3)
<i>Control</i>								
Pre	121(6)	0.84(0.01)	702(59)	9.4(0.5)	145(5)	0.88(0.02)	959(84)	13.4(0.4)
Post	122(5)	0.82(0.01)	698(57)	9.7(0.5)	145(5)	0.87(0.01)	984(81)	13.9(0.3)
60 rpm								
<i>Training</i>								
Pre	129(4)	0.88(0.01)	547(32)	10.8(0.5)	152(4)	0.93(0.01)	760(43)	13.8(0.4)
Post	127(4)	0.88(0.01)	551(30)	10.4(0.6)	148(4)	0.93(0.01)	767(44)	13.9(0.3)
<i>Control</i>								
Pre	112(4)	0.88(0.01)	639(54)	9.7(0.3)	141(5)	0.90(0.01)	925(82)	13.9(0.4)
Post	114(3)	0.86(0.01)	646(54)	9.6(0.2)	140(4)	0.89(0.01)	924(76)	14.0(0.4)

RER respiratory exchange ratio, REE rate of energy expenditure, RPE rate of perceived exertion

* Different from pre, $p < 0.05$

** Different from pre, $p < 0.01$

The difference between pre and post measurements is different from the corresponding value in the control group, $p < 0.01$

neuromuscular responses to strength training and the transfer between the strength trained movements and other movements is limited (Carroll et al. 2001). Still, it is generally

recognized that substantial plasticity within the neuromuscular system allows a considerable effect of strength training on motor control. Strength training may down-regulate

Ib afferent feedback (autogenous inhibitory feedback) from the force-sensitive Golgi tendon organs at a given constant level of stimulation (Aagaard et al. 2000). Such a down-regulation could be due to less tendon organ deformation as a result of increased tendon stiffness following strength training (Kubo et al. 2002). If this is so, perhaps then strength training reduces the part of the sensed effort that is related to the muscle/tendon load, thereby causing subjects to decrease the freely chosen pedal rate, despite the fact that this increases the force in each pedal thrust. Another possibility is that the output rate of the central pattern generators is somehow reduced by heavy strength training. The central pattern generators are neural networks located in the spinal cord and being capable of generating rhythmic limb movement such as pedaling (Zehr 2005). According to the best of our knowledge an effect of strength training on central pattern generator output or function has not been reported before. However, it has been suggested that daily balance training in healthy infants affected the central pattern generators involved in postural adjustments (Hadders-Algra et al. 1996). The suggestion was made on basis of, e.g., kinematic and surface electromyographic data showing that the training changed the muscle activation pattern in a way that the selection of the most complete response pattern was facilitated during horizontal translations of the seated infants. For the interpretation of the data it was assumed that postural adjustments to external displacements are generated by central pattern generators. Because of the obvious difference in subjects and training regimens between the study by Hadders-Agra et al. (1996) and the present study, results cannot be directly compared. Nevertheless, the previously published results by Hadders-Agra et al. (1996) support the point made here that central pattern generators involved in pedaling could have been modified by the heavy strength training in the present study.

Strength training did not change the economy of submaximal cycling at 60 rpm. In contrast to this, it has been reported that untrained males following 8 weeks of strength training improved their cycling economy ($\Delta\text{VO}_2/\Delta$ power output) at 70 rpm at exercise intensity comparable to the 57% of W_{max} used in the present study (Loveless et al. 2005). Still, at lower exercise intensity the authors reported similar values for economy before and after the strength training period. The mechanisms responsible for the increased economy remain unknown, although Loveless et al. (2005) speculated that recruitment of fewer type II muscle fibers at high intensity cycling following strength training could reduce the oxygen cost of cycling. Such an explanation seems reasonable since type II fibers have been shown to be less efficient than type I fibers (Coyle et al. 1992; Hansen et al. 2002; Mogensen et al. 2006). In the present study, strength training reduced freely chosen pedal rate and this appears to be the reason for the reduced VO_2 .

This indicates a possible transfer from strength training, via changed motor behavior to reduced rate of energy expenditure. That pre and post heart rate values during cycling at a fixed power output and pedal rate were similar within each group indicated that maximal aerobic power was unchanged from the beginning to the end of the study for both groups.

Cycling at preset pedal rate and at freely chosen pedal rate are not identical motor tasks. It is therefore possible that oxygen uptake and energy expenditure are not the same at the two tasks, even if the absolute pedal rates happen to be identical. Still, the pedal rate at 60 rpm had to be maintained by the subjects on basis of feed back from a display. In practice that means that the subjects pedaled, e.g., between 59 and 61 rpm, whereas during freely chosen pedal rate the subjects adapted to their freely chosen pedal rate within the first 2–3 min and maintained this within 4 rpm throughout the bout. In general, the difference between the tasks of pedaling at a preset pedal rate and at freely chosen pedal rate is not considered to affect the findings of the present study.

Finally, it should be stressed that the present study was designed to elucidate aspects of voluntary motor behavior among healthy subjects rather than aspects of cycling performance among trained cyclists. It is known that the relationship between oxygen uptake and pedal rate becomes more flat when power output increases (Foss and Hallén 2004). This means that trained cyclists exercising at higher absolute power outputs than the present subjects would perhaps not obtain a lower energy expenditure after a period of strength training even if they reduced their freely chosen pedal rate to the same extent as seen here. Thus, since the subjects in the present study were not trained cyclists, new studies should be conducted to reveal whether heavy strength training also affects elite cyclists to reduce their freely chosen pedal rate and energy expenditure during submaximal cycling.

In conclusion, heavy strength training caused healthy subjects to choose an approximately 9 rpm lower pedal rate during submaximal cycling. This was accompanied by a $\sim 3\%$ lower rate of energy expenditure.

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