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Cyclists' Improvement of Pedaling Efficacy and Performance After Heavy Strength Training

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The authors tested whether heavy strength training, including hip-flexion exercise, would reduce the extent of the phase in the crank revolution where negative or retarding crank torque occurs. Negative torque normally occurs in the upstroke phase when the leg is lifted by flexing the hip. Eighteen well-trained cyclists either performed 12 wk of heavy strength training in addition to their usual endurance training (*E+S*; $n = 10$) or merely continued their usual endurance training during the intervention period (*E*; $n = 8$). The strength training consisted of 4 lower body exercises (3×4 –10 repetition maximum) performed twice a week. *E+S* enhanced cycling performance by 7%, which was more than in *E* ($P = .02$). Performance was determined as average power output in a 5-min all-out trial performed subsequent to 185 min of submaximal cycling. The performance enhancement, which has been reported previously, was here shown to be accompanied by improved pedaling efficacy during the all-out cycling. Thus, *E+S* shortened the phase where negative crank torque occurs by $\sim 16^\circ$, corresponding to $\sim 14\%$, which was more than in *E* ($P = .002$). In conclusion, adding heavy strength training to usual endurance training in well-trained cyclists improves pedaling efficacy during 5-min all-out cycling performed after 185 min of cycling.

Keywords: bicycling, endurance performance, pedaling technique, resistance training, weight training

In the sport of competitive cycling, there is an ongoing effort to develop training methods to further enhance performance. Recently, it has been reported that concurrent heavy strength training and endurance training in well-trained cyclists result in enhanced cycling performance.¹⁻⁴ Other research groups have previously failed to find a similar positive effect of strength training on performance in trained cyclists.^{5,6} In one of our previous articles, cycling performance was determined as the power output in a 5-minute all-out trial performed subsequent to 185 minutes of submaximal cycling.³ Despite the fact that our previous publications have not pointed out a particular reason for the enhanced performance, we have discussed that it may be a result of the specific strength-training exercises performed. Thus, the 1-leg hip-flexion exercise performed in this study, but not in previous studies, may somehow have made a difference and contributed to the enhanced performance. For example, it is possible that strengthened hip-flexor muscle-tendon systems would allow cyclists to more effectively lift the mass of the leg during the recovery or

upstroke phase. This may reduce the extent of the phase in the crank revolution in which negative or retarding crank torque occurs: the current study investigates this. The upstroke phase is when the leg is lifted by flexing the hip and the crank turns between angles of 180° and 360° . For definition, crank angles of 0° and 360° represent the top dead center of the crank revolution.

In support of the importance of the upstroke phase during pedaling, it has been reported that competitive cyclists during a ride to exhaustion at 80% of their maximal aerobic power output gradually produced more negative or retarding pedal force in this particular phase of the crank revolution. This increased the demand for forces during the propulsive or downstroke phase and, overall, caused the cyclists' pedaling to become less effective.⁷

To evaluate changes in pedaling efficacy, the crank torque was measured in both a prolonged cycling bout and in the subsequent all-out trial in the previously mentioned study, from which we have already reported some data.³ These crank-torque data analyses can consequently be regarded as a part of a larger investigation in which effects of heavy strength training on cycling performance were examined. To our knowledge, the current report is the first to describe the influence of heavy strength training on pedaling efficacy.

The purpose of the current study was to investigate whether enhanced cycling performance after strength training was accompanied by an improved pattern of crank-torque application, reflecting improved pedaling

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efficacy. Specifically, we tested the hypothesis that heavy strength training, including hip-flexion exercise, would reduce the extent of the phase in the crank revolution where negative or retarding crank torque occurs. This phase constitutes a part of the upstroke phase where the leg is lifted by flexing the hip.

Materials and Methods

Participants

Twenty well-trained cyclists, competing at the Norwegian national level, volunteered to participate in the study. Written informed consent was obtained from the participants, none of whom had performed any strength training during the preceding 6 months. The study conformed to the standards set by the Declaration of Helsinki, and the procedures were approved by the regional committee of Southeast Norway of the National Committees for Research Ethics in Norway. Due to technical problems, data from 2 of the participants were lost. Data from 18 participants are therefore reported here.

Participants were divided into a test group and a control group. The participants in the test group (*E+S*; $n = 10$ [10 men], age 27 ± 7 y, height 1.83 ± 0.07 cm, body mass 76.8 ± 9.0 kg) performed 12 weeks of heavy strength training in addition to their usual endurance training. The participants in the control group (*E*; $n = 8$ [6 men, 2 women], age 30 ± 7 y, height 1.81 ± 0.08 m, body mass 75.8 ± 8.9 kg) merely continued their usual endurance training during the intervention period. The intervention was carried out during the preparation period for the competition season.

Training

The endurance training was planned and completed by the participants without any interference from the researchers. It primarily consisted of cycling, but some cross-country skiing was also performed by some participants (a maximum of 10% of the total training duration). Duration and intensity of the endurance training were determined from Polar heart-rate monitor (Electro Oy, Kempele, Finland) recordings. Thus, the performed endurance training was divided into 5 heart-rate zones: (1) 60% to 72%, (2) 73% to 82%, (3) 83% to 87%, (4) 88% to 92%, and (5) 93% to 100% of maximal heart rate. A detailed overview of the endurance training distributed in these 5 heart-rate zones is presented in Table 1 in a previous publication.¹ Briefly, the total duration of the training (~ 12 h/wk) and the distribution of this training within the 5 heart-rate zones were similar for *E+S* and *E*. Training in zone 1 constituted ~ 6.7 h/wk, while ~ 2.2 and 1.0 h/wk was performed in zones 2 and 3, respectively. No significant difference between the 2 groups was observed when comparing total training duration throughout the 12-week study period, including the heavy strength training, as well as core-stability training and stretching

(151 ± 13 h and 138 ± 13 h, respectively; $P = .47$). The latter was apparently due to a slightly, though statistically nonsignificantly, longer endurance-training duration in *E*.

Heavy strength training performed by participants in *E+S* was carried out twice a week and primarily targeted the leg muscles. Adherence was high, with participants completing $97\% \pm 1\%$ of the prescribed training. The training has previously been described in detail.¹⁻³ Briefly, the heavy strength training was systematically performed first on days when both strength training and endurance training were carried out. The intention of the training was to improve cycling performance, so primarily unilateral exercises were applied targeting lower limb muscles associated with cycling. Peak positive pedal force during pedaling occurs at a knee angle of approximately 90° ,⁸ and exercises were therefore performed with a knee angle between 90° and almost-full knee extension. In addition, since cyclists use legs alternately during cycling, 1-leg exercises were chosen whenever it was practical. The heavy strength training was carried out with focus on maximal intended acceleration in the concentric phase (lasting around 1 s), while the eccentric phase was performed more slowly (lasting around 2–3 s). At the start of each strength-training session, participants performed an ~ 10 -minute warm-up at self-selected intensity on a cycle ergometer. This was followed by 2 or 3 warm-up sets of half-squat with gradually increased load. The strength-training exercises performed thereafter were half-squat, leg press with 1 leg at a time, hip flexion with 1 leg at a time, and ankle plantar flexion. Photos of the exercises have been published elsewhere.² All participants were carefully supervised by 1 of the researchers during all workouts for the first 2 weeks and thereafter at least once every second week throughout the rest of the intervention period. During the first 3 weeks, cyclists trained with 10-repetition-maximum (RM) sets (ie, with 10 repetitions in each set) at the first weekly session and 6RM sets at the second weekly session. During the following 3 weeks, the loads in the sets were adjusted to 8RM and 5RM for the first and second weekly sessions, respectively. Finally, during the last 6 weeks, the loads in the sets were adjusted to 6RM and 4RM, respectively. Assistance during the last repetition was allowed. During every training session, 3 sets of each training exercise were performed.

Testing

Testing was completed before and after the intervention period in a number of sessions carried out on separate days as follows: (1) measurement of maximal strength, (2) measurement of maximal oxygen uptake (VO_{2max}), and (3) prolonged cycling followed by a 5-minute all-out trial. To maximize the possibility of detecting the systematic effects of the intervention, great care was taken to replicate the testing protocol from the preintervention testing during the postintervention testing. Thus, the preparations for the tests, the conditions during the tests, and the order of tests were the same. Furthermore,

the tests were performed at the same time of day to avoid circadian influence.

Maximal leg-extensor muscle strength was determined as 1RM loading during a unilateral leg-press maneuver using the dominant leg. Before the pretest, 2 familiarization sessions were conducted with the purpose of instructing the cyclists in the proper technique and testing procedure. Strength tests were always preceded by a 10-minute warm-up bout on a cycle ergometer. After warm-up, the cyclists performed a standardized protocol consisting of 3 sets with a gradually increasing load (40%, 75%, and 85% of predicted 1RM) and a decreasing number of repetitions (10, 7, and 3). The first 1RM attempt was performed with a load approximately 5% below the predicted 1RM load. After each successful attempt, the load was increased by 2%–5% until the cyclist failed to lift the same load after 2 or 3 consecutive attempts. The rest period between attempts was 3 minutes. The preintervention and postintervention tests were conducted using the same equipment with identical positioning of the cyclist relative to the equipment and monitored by the same experienced investigator. The postintervention test for strength was conducted 3 to 5 days after the last strength-training session. Maximal strength in hip-flexor muscles was not measured directly. Instead, progress in the hip-flexion exercise was determined indirectly by comparing the training load at 6RM in the first and the last week of the training period.

All cycling tests were performed on the same Lode Excalibur Sport electromagnetically braked cycle ergometer (Lode BV, Groningen, The Netherlands), which was adjusted according to each cyclist's preferences for seat height, distance between seat and handlebars, and horizontal distance between vertical lines through the tip of the seat and the bottom bracket. Individual settings of the cycle ergometer were noted at the pretest, and the exact same settings were used at the posttest. The cyclists were allowed to choose their preferred cadence during all cycling tests, and they used their own cycling shoes and pedals.

$\text{VO}_{2\text{max}}$ was measured in an incremental cycle-ergometer test that was initiated with 1 minute of cycling at a power output corresponding to 3 W/kg (rounded down to the nearest 50 W). The power output was then increased by 25 W every 1 minute until exhaustion. When the cyclists indicated that they were not able to manage another 25-W increase in power output, they were encouraged to simply continue cycling at the current power output as long as possible (usually for 30–90 s). They were verbally encouraged to continue as long as possible. Oxygen uptake and respiratory-exchange ratio were measured (30-s sampling times) using a computerized metabolic system with a mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany). The gas analyzers were calibrated against certified calibration gases of known concentrations before every test. The flow turbine (Triple V, Erich Jaeger) was calibrated before every test with a 3-L, 5530 series calibration syringe (Hans Rudolph,

Kansas City, MO). $\text{VO}_{2\text{max}}$, along with the complementary data, was calculated as the average of the 2 highest VO_2 measurements. Heart rate was measured using a Polar heart-rate monitor (Electro Oy, Kempele, Finland). The criteria used to ensure that $\text{VO}_{2\text{max}}$ values were reached were blood lactate concentrations >8 mmol/L during the first 2 minutes of recovery (Lactate Pro LT-1710, Arcray Inc., Kyoto, Japan), respiratory-exchange ratio at test termination >1.05 , and rating of perceived exertion ≥ 18 using Borg's scale of 6 to 20. Average values across the 2 groups on these criterion variables at the pretest were 12.5 ± 2.4 , 1.08 ± 0.03 , and 19.0 ± 0.5 mmol/L, respectively. At the posttest, the values were 13.3 ± 1.9 , 1.08 ± 0.03 , and 19.1 ± 0.6 mmol/L, respectively. No differences were observed between the 2 groups. W_{max} was calculated at baseline as the average power output during the last 2 minutes of the incremental test. This W_{max} was used to calculate the submaximal power output applied during the prolonged cycling.

Prolonged cycling was performed as 185 minutes of cycling at 44% of W_{max} and followed by a 5-minute all-out trial. W_{max} determined in the incremental test at preintervention amounted to 409 ± 32 W in *E+S* and 407 ± 76 W in *E*. The average power outputs during the prolonged cycling were consequently preset to 180 ± 14 W and 179 ± 34 W in *E+S* and *E*, respectively, in the preintervention and postintervention tests. The apparently modest power output was chosen based on previous research showing that competitive road cyclists spend nearly half of racing time riding at a power output of <150 W.⁹ During the prolonged cycling, the ergometer was in a cadence-independent or constant-Watt-production mode so that the preset power output was not affected by the cyclists' choice of cadence. During the first 10 min, the cyclists were required to maintain a cadence of 60 rpm. During the rest of the prolonged cycling, they could freely choose a cadence. Cyclists were allowed to occasionally stand in the pedals during the latter part of the prolonged cycling, but not during the final 5-minute all-out trial. During the prolonged cycling, the cyclists were allowed to consume a sport drink containing 75 g/L of carbohydrates, ad libitum, to maintain fluid balance and mimic race conditions. In addition, subjects were cooled with an air fan. VO_2 , respiratory-exchange ratio, heart rate, cadence, rating of perceived exertion, and blood lactate concentration were determined during 5-minute periods every half-hour throughout the prolonged cycling. These results have been reported together with details on measurement methods.³

Cycling performance was determined in a 5-minute all-out trial performed 2 minutes after termination of the 185 minutes of prolonged cycling. In line with an earlier study,¹⁰ the 5-minute all-out trial was chosen as a functional measure of the capacity to perform very intensive cycling, such as is required during a breakaway attempt, crosswind cycling, or steep uphill cycling, all of which may be decisive situations in a road race. For the 5-minute all-out trial, the ergometer was switched to

the cadence-dependent mode, in which the power output increases with increasing cadence according to the following equation: $W = L \times \text{rpm}^2$, where W is the power output, rpm is the cadence, and the constant, L , was set to 0.044. L determines the electronic gearing of the system. Based on results from a previous study,¹⁰ average power output during the 5-minute all-out trial was predicted to be 360 to 400 W. Because the preferred cadence for many cyclists at this intensity is around 90 to 95 rpm, L was set to 0.044. As an example, a constant cadence of 93 rpm would result in an average power output of 381 W during the 5-minute all-out trial. All cyclists were encouraged to produce as high an average power output as possible during the 5-minute all-out trial. They received feedback regarding power output and time elapsed, but not heart rate and cadence.

Crank torque was calculated continuously by the Lode ergometer software during both prolonged cycling and the all-out trial. Thus, for each participant, effective crank-torque values for left and right crank separately, at every second crank-angle degree, in every single crank revolution, were sampled. To reduce this large amount of data, average values across certain cycling periods (see Results) were calculated from the following 3 selected crank-torque-curve characteristics: peak positive or propulsive crank torque, T_{pos} ; peak negative or retarding crank torque, T_{neg} ; and phase of the crank cycle with negative crank torque, P_{neg} (Figure 1).

Statistical Analysis

Pearson product-moment correlation coefficients (R^2), linear regression, and paired-samples and 2-sample t tests were used wherever it was appropriate. Statistics were calculated in Excel 2010 (Microsoft Corp, WA). Data are presented as mean \pm SD unless otherwise indicated. Statistical significance was set at $P < .05$.

Results

The maximal strength in the leg-extensor muscles in $E+S$, reflected by 1RM in leg press with the dominant leg, was 142 ± 34 kg at preintervention and 175 ± 39 kg at postintervention ($P < .001$). For comparison, the maximal strength in E was 139 ± 50 kg at preintervention and 128 ± 51 kg at postintervention ($P = .03$). The size of change was larger in $E+S$ than in E ($P < .001$). The load applied by $E+S$ in the 6RM hip-flexion training exercise, reflecting the strength of the hip-flexor muscles, increased $54\% \pm 34\%$, from 56 ± 28 kg in week 1 to 83 ± 34 kg in week 12 ($P < .001$).

During the prolonged submaximal cycling, the cadence remained similar across the period ranging from the 10th to the 185th minute in both $E+S$ and E and amounted to 79 ± 7 rpm at preintervention and 79 ± 6 rpm at postintervention in $E+S$. For comparison, the cadences in E at preintervention and postintervention were 81 ± 9 and 80 ± 9 rpm, respectively. There were no statistically significant differences between the 2 groups regarding the changes from preintervention to postintervention in the selected crank-torque characteristics (Table 1).

During the 5-minute all-out trial, the power output in $E+S$ was 372 ± 27 W at preintervention and 399 ± 38 W at postintervention ($P = .007$). For comparison, the power output in E remained similar throughout the study period: 385 ± 68 W and 380 ± 68 W, respectively ($P = .63$). The increase was larger in $E+S$ than in E ($P = .02$). The cadence during this cycling performance test was 93 ± 4 rpm at preintervention and 95 ± 4 rpm at postintervention in $E+S$. In E , the cadence was 93 ± 8 rpm at both measurements. The results of the analysis of crank torque during the 5-minute all-out trial are presented in Tables 1 and 2. In brief, peak positive crank torque (T_{pos}) increased more from preintervention to postintervention

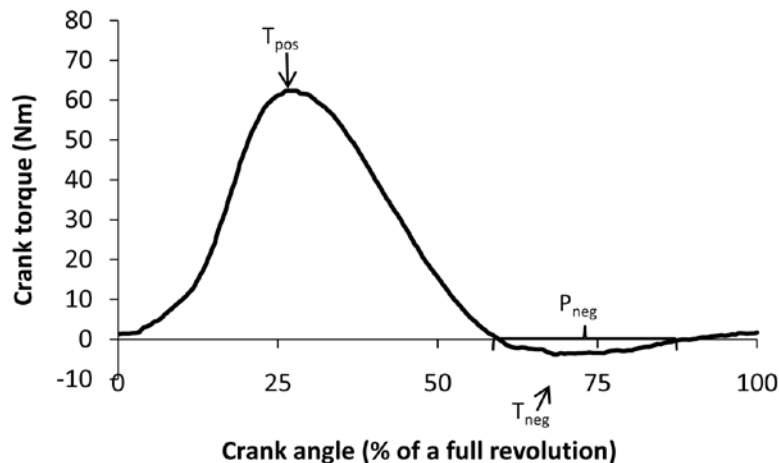


Figure 1 — Crank-torque curve with selected characteristics. This data example from one of the cyclists represents a single random crank-arm (right) revolution during one of the 5-min all-out trials. The following selected characteristics are indicated on the curve: T_{pos} , peak positive crank torque; T_{neg} , peak negative crank torque; P_{neg} , phase with negative crank torque.

Table 1 Selected Crank Torque Characteristics During the Initial 185 min of Submaximal Cycling and the Subsequent 5-min All-Out Cycling Trial, Mean \pm SD

	From 5th to 10th min during submaximal cycling at 60 rpm			From 10th to 185th min during submaximal cycling at freely chosen cadence			During 5-min all-out trial		
	T _{pos} , Nm	T _{neg} , Nm	P _{neg} , °	T _{pos} , Nm	T _{neg} , Nm	P _{neg} , °	T _{pos} , Nm	T _{neg} , Nm	P _{neg} , °
<i>E+S</i> (n = 10)									
pre	56 \pm 6	-8 \pm 2	146 \pm 15	53 \pm 6	-12 \pm 2	161 \pm 4	71 \pm 5	-8 \pm 3	117 \pm 19
post	57 \pm 6	-7 \pm 2	138 \pm 26	53 \pm 6	-12 \pm 2	158 \pm 6	73 \pm 5	-7 \pm 3	101 \pm 22
Δ	1 \pm 2	0 \pm 1	-8 \pm 18	0 \pm 3	0 \pm 1	-3 \pm 5	2 \pm 2*	1 \pm 2	-16 \pm 11**
<i>E</i> (n = 8)									
pre	56 \pm 8	-9 \pm 1	147 \pm 16	53 \pm 9	-13 \pm 2	158 \pm 5	75 \pm 8	-8 \pm 5	109 \pm 13
post	57 \pm 7	-8 \pm 2	148 \pm 15	54 \pm 8	-12 \pm 2	158 \pm 6	73 \pm 7	-8 \pm 4	111 \pm 10
Δ	1 \pm 2	0 \pm 1	1 \pm 7	1 \pm 2	1 \pm 2	0 \pm 3	-1 \pm 2	1 \pm 1	2 \pm 6

Abbreviations: T_{pos}, peak positive crank torque; T_{neg}, peak negative crank torque; P_{neg}, phase with negative crank torque; *E+S*, cyclists performing heavy strength training in addition to their usual endurance training; *E*, cyclists performing their usual endurance training.

**Significantly different from *E* ($P = .002$). *Significantly different from *E* ($P = .007$).

in *E+S* than in *E* ($P = .007$). Still, the increase from pre-intervention to postintervention in *E+S* was modest (~ 2 Nm, corresponding to $\sim 3\%$). Furthermore, the phase with negative crank torque (P_{neg}) was shortened more from preintervention to postintervention in *E+S* than in *E* ($P = .002$; Table 1). Peak negative crank torque (T_{neg}) was unchanged in both groups. Similar results for T_{pos}, T_{neg}, and P_{neg} were obtained by an alternative type of analysis with correlation and regression (Figure 2, Table 2). In Table 2, these crank-torque-characteristic variables are represented by *a* values from the linear-regression equations. Furthermore, the differences between *E+S* and *E* in the changes of these groups from preintervention to postintervention were similar to the results from the analysis where T_{pos}, T_{neg}, and P_{neg} values were calculated as averages across the trial (Table 1).

Body mass in both *E+S* and *E* remained unchanged from preintervention to postintervention. VO_{2max} in *E+S* was 5118 \pm 538 mL/min at preintervention and 5361 \pm 683 mL/min at postintervention. For comparison, VO_{2max} in *E* was 4986 \pm 967 mL/min at preintervention and 5196 \pm 977 mL/min at postintervention. The amount of change in values from preintervention to postintervention was not different between the 2 groups.

Discussion

The most notable finding of the current study was that heavy strength training caused well-trained cyclists to improve their pedaling efficacy and concomitantly enhance their performance during all-out cycling. The strength training was performed throughout 12 weeks and included hip-flexion exercise. Improved pedaling efficacy was reflected by a reduction of the phase with negative

or retarding crank torque (P_{neg}) that occurs during the upstroke part of the crank revolution. Performance was determined as average power output during a 5-minute all-out trial performed subsequent to 185 minutes of submaximal cycling.

Recently, possible adaptive mechanisms accounting for enhanced endurance performance subsequent to strength training were reviewed.¹¹ Among the proposed mechanisms were improved neural function and increased tendon stiffness, which both have the potential to increase the rate of force development. An increased rate of force development of the hip-flexor muscles, perhaps especially the iliopsoas muscles, obviously has the potential to contribute to the observed improvement of pedaling efficacy. Other researchers have reported that the iliopsoas muscle is an important contributor during pedaling.¹² The rectus femoris muscle, which crosses the hip joint like the iliopsoas muscle, but in addition crosses the knee joint, is considered a top transition-extensor muscle, where "top" refers to the top dead center of the crank revolution.¹³ Increased rate of force development in the hip-flexor muscles would reduce the time from muscle activation to production of a force of sufficient magnitude to flex the hip, lift the leg mass against gravity, and eventually relieve the pedal from the mass of the leg. Related to this is the electromechanical delay, which is the delay between the onset of electrical activity and measurable force. This delay is suggested to be associated with the time required to stretch the muscle's series elastic component. It has been reported that isometric knee-extension training at 70% of maximal voluntary contraction reduced electromechanical delay by 18%.¹⁴ If the electromechanical delay is, for example, 100 milliseconds,^{15,16} it corresponds to 57° of crank revolution during

Table 2 Variables in the Linear-Regression Equation and R², Mean ± SD

	T _{pos} , Nm			T _{neg} , Nm			P _{neg} , °		
	b	a	R ²	b	a	R ²	b	a	R ²
<i>E+S</i> (n = 10)									
pre	.005 ± .017	70 ± 4	.100 ± .144	-.004 ± .004	-7 ± 3	.076 ± .079	.012 ± .064	114 ± 26	.074 ± .071
post	-.005 ± .008	75 ± 5	.047 ± .061	-.006 ± .005	-6 ± 2	.128 ± .162	.015 ± .059	97 ± 28	.061 ± .059
Δ	-.011 ± .017	5 ± 4*		-.002 ± .004	1 ± 2		.004 ± .027	-17 ± 11***	
<i>E</i> (n = 8)									
pre	.001 ± .015	74 ± 8	.074 ± .091	-.004 ± .005	-8 ± 4	.139 ± .116	.005 ± .060	108 ± 20	.098 ± .070
post	.000 ± .014	73 ± 5	.075 ± .075	-.002 ± .004	-7 ± 4	.130 ± .111	.000 ± .067	111 ± 17	.114 ± .095
Δ	-.001 ± .011	-1 ± 4		.002 ± .003	0 ± 1		-.006 ± .050	3 ± 14	

Abbreviations: T_{pos}, peak positive crank torque; T_{neg}, peak negative crank torque; P_{neg}, phase with negative crank torque; *E+S*, cyclists performing heavy strength training in addition to their usual endurance training; *E*, cyclists performing their usual endurance training.

Note: *b* and *a* in $y = bx + a$. The linear regressions were performed on the crank-torque characteristics of T_{pos}, T_{neg}, and P_{neg} (y) plotted as a function of crank-revolution number (x) during the 5-min all-out cycling trial that was performed subsequent to 185 min of submaximal cycling. The reader is referred to Figure 2 for an example of data analysis.

*Significantly different from *E* ($P = .01$). **Significantly different from *E* ($P = .006$).

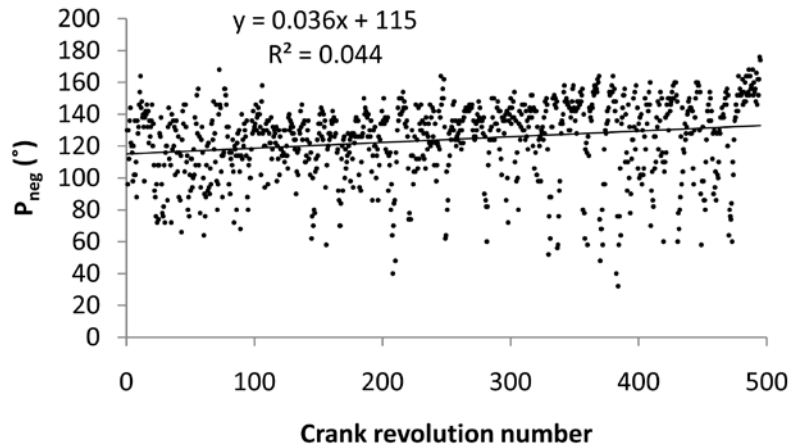


Figure 2 — Phase with negative crank torque, P_{neg} , as a function of crank-revolution number in a 5-min all-out trial. This data example is from a representative cyclist performing the cycling performance trial at postintervention. The regression equation, of the form $y = bx + a$, includes b that represents the slope and reflects the development over time. It also includes a , which represents the y intercept and reflects the P_{neg} value at the beginning of the trial.

pedaling at 95 rpm. Furthermore, an 18% reduction of the delay corresponds to 10° , which can be compared with the reduction of 16° of the phase with negative crank torque observed in the current study. It is also possible that the strength training improved muscle-activation timing. Future studies applying electromyography to measure muscle activation could elucidate this. It could also be argued that the hip-flexor muscles became more fatigue-resistant after the strength training. However, if this occurred and affected performance, it would perhaps be expected that the phase with negative crank torque would increase less as a function of time during the 5-minute all-out trial after strength training. This should have been reflected by reduced slopes in the regression equations (b values). However, results from the regression analyses did not support this (Table 2). In addition, on a group level, neither preintervention nor postintervention b values were significantly different from zero. The observation of slightly increased peak positive crank torque during the postintervention 5-min all-out trial in the strength-trained cyclists is a predictable consequence when the produced power output is increased.¹⁷

Negative crank torque in the upstroke phase is overcome by additional positive crank torque in the downstroke phase during cycling at a given power output. Intuitively, the phase with negative crank torque should thus not be too long. A reduction of the phase with negative torque decreases the demand on the leg-extensor muscles, which are active in the downstroke. Such a reduction may be considered a performance improvement.¹⁷ Still, it is not necessarily ideal that the negative crank torque be completely eliminated. And even trained cyclists with years of training experience produce negative crank torque.¹⁸ The reason could be that some phase with limited activity in the hip-flexor muscles, which may result in negative crank torque

during the upstroke, might be beneficial, in particular if these muscles are prone to be overloaded and fatigued and perhaps are even limiting performance. Furthermore, having well-timed phases with limited hip-flexor muscle activity in the top and bottom transition phases between upstroke and downstroke limits the likeliness of eccentric contraction in the hip-flexor muscles. In connection with this, it is worth noting that no statistically significant training-induced reduction of the phase with negative or retarding crank torque was detected during submaximal cycling in the current study. These results differed from data for the final 5-min all-out trial, which should be further examined in future research.

The effect of the strength training depends on a number of variables being directly associated with the performed training. Examples are the load, the number of repetitions, and the exercises, as well as the muscles involved. Other examples are the duration of the training period, the number of sets in each training session, and the order in which strength- and endurance-training sessions are performed during a day. Consequently, there is an almost infinite number of ways to design strength-training programs for endurance athletes. This also makes it challenging to compare training adaptations between different studies and interpret the results. Nevertheless, an interpretation of the current results might be that hip-flexion exercise in particular plays a key role in improving pedaling efficacy and performance during intensive cycling. Thus, it is possible that strengthened hip-flexor muscle-tendon systems allow cyclists to lift the leg mass in a more effective way during the upstroke phase and thereby reduce the extent of the phase of the crank revolution in which negative or retarding crank torque occurs. The absence of specific hip-flexion exercise in previous longitudinal intervention studies performed in trained cyclists might contribute to explain why at least some

of these studies were not able to observe any increase in endurance-cycling performance.^{5,6}

An interesting thought is that time-consuming strength training could be bypassed by specific pedaling technique training or simply by increased focus on more effective pedaling during cycling in the effort to improve performance. In support of this, a positive relationship between effective force application and cycling economy has been reported in a cross-sectional study involving cyclists and triathletes.¹⁸ However, it has also been reported from intervention studies that imposed pull in the upstroke phase results in decreased gross efficiency¹⁹ and net mechanical efficiency.²⁰ It thus appears that at present the most obvious way for well-trained cyclists to improve pedaling efficacy and performance during intensive cycling is through heavy strength training that includes hip-flexor exercise.

Pedaling efficacy was not significantly improved during submaximal cycling for the cyclists in *E+S* in the current study, which was unlike what was observed during the 5-minute all-out trial. However, at the same time, the strength-training intervention actually led to a greater reduction in VO_2 than endurance training alone during the last hour of the 185-minute submaximal cycling bout.³ The latter reflects improved cycling economy. This is yet another example, in addition to those already cited,^{19,20} that there is not necessarily a clear association between improvement of cycling economy and improvement of pedaling efficacy.

In the current study, cadence was stable across time during the prolonged submaximal cycling bout in the pretest and, furthermore, remained unaffected by the strength-training intervention. Previously, it has been reported that cadence decreased throughout 2 hours of submaximal cycling before a 5-week strength-training period.²¹ After the strength-training intervention, cadence decreased in the first hour of submaximal cycling with no further decrease in the subsequent hour. The disparate results of training may arise from different athletes analyzed, since Hausswirth et al examined well-trained triathletes while the current study examined well-trained cyclists who hypothetically may demonstrate a greater fatigue resistance to prolonged cycling than triathletes.

Rather than randomly distributing participants to the 2 different groups in the current study, the participants could choose whether they would be in *E+S* or *E*. The reason is that it is difficult to gather enough well-trained competitive cyclists who are willing to be allocated randomly to extensive participation in 3 months of strength training or control testing. Still, it could be argued that in a study of this type the limitation of not randomizing the participants to the experimental groups is outweighed by having a sufficient number of participants and high adherence.

The applied perspective of the current study is that trained cyclists apparently can improve their pedaling efficacy and concomitantly their all-out cycling performance by performing concurrent endurance and strength training that involves hip-flexion exercises and heavy

loads. To the best of our knowledge, this is the first study to investigate the effect of heavy strength training on pedaling efficacy in trained cyclists.

In conclusion, 12 weeks of heavy strength training including hip-flexion exercise enhanced well-trained cyclists' performance. Performance was determined as average power output in a 5-minute all-out trial performed subsequent to 185 minutes of submaximal cycling. A 7% performance enhancement during the 5-minute all-out cycling trial was accompanied by improved pedaling efficacy. Thus, the particular phase in the upstroke phase of the crank revolution where negative or retarding crank torque occurs (P_{neg}) was shortened by $\sim 16^\circ$, corresponding to $\sim 14\%$. In addition, the strength-trained cyclists increased their peak positive or propulsive crank torque (T_{pos}) by $\sim 3\%$.

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