Strength Training Affects Tendon Cross-Sectional Area and Freely Chosen Cadence Differently in Noncyclists and Well-Trained Cyclists

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Abstract

Rønnestad, BR, Hansen, EA, and Raastad, T. Strength training affects tendon cross-sectional area and freely chosen cadence differently in noncyclists and well-trained cyclists. *J Strength Cond Res* 26(1): 158–166, 2012—The effects of strength training on freely chosen cadence and physiological responses in cyclists and recreationally active individuals were investigated. Well-trained cyclists were assigned to either usual endurance training combined with strength training (C-ES; $n = 11$) or usual endurance training only (C-E; $n = 9$). Recreationally active individuals (R-S; $n = 7$) performed the same strength training as C-ES did (4 lower body exercises, 3×4–10 repetition maximum [RM], twice a week for 12 weeks). The R-S and C-ES increased 1RM to a similar extent after 4 and 12 weeks ($p < 0.01$), whereas 1RM remained unchanged in C-E. Only R-S increased patellar tendon cross-sectional area (CSA; $7 \pm 1\%$, $p < 0.001$). After 4 weeks, R-S reduced freely chosen cadence, oxygen consumption, heart rate, rating of perceived exertion, and blood lactate concentration during cycling at 125 W. These responses remained reduced throughout the intervention period ($p < 0.05$). No significant changes were observed in these physiological variables in C-ES and C-E. In conclusion, freely chosen cadence during submaximal cycling was reduced in recreationally active individuals after a period of strength training but was not reduced in well-trained cyclists. The reduced freely chosen cadence may be associated with the observed increase in patellar tendon CSA through a morphological-sensory-motor interaction. A practical application is that heavy strength training can reduce freely chosen cadence during submaximal cycling and thereby improve cycling economy in recreationally active individuals, whereas other mechanisms should account for improved performance after strength training in well-trained cyclists.

Key Words cycling economy, rpm, preferred pedaling rate, resistance training

Introduction

It is a common quest among endurance athletes to minimize exercise oxygen consumption ($\dot{V}O_2$), which reflects energy turnover and work economy during constant workload conditions. Improved work economy during prolonged endurance activity is associated with increased overall endurance performance (2). Athletes' movement patterns affect $\dot{V}O_2$ and energy turnover. Examples of movement patterns are step rates in walking and running. The freely chosen step rates during walking and running have been shown to converge with the energetically optimal step rates (7,24). In contrast, during submaximal cycling, which represents another rhythmical movement, the freely chosen cadence has been found to be higher than the energetically optimal cadence for both recreationally active individuals and well-trained cyclists (9,11). This phenomenon has been considered a paradox because an energetically nonoptimal cadence may impair performance (17).

It has been shown that the indirect subjective performance measurement of perceived exertion during 150 minutes of prolonged submaximal cycling increased less during cycling at a relatively low energetically optimal cadence compared with a higher, freely chosen cadence (12). Furthermore, Hansen et al. (14) found that 12 weeks of strength training, in addition to increasing maximal strength, reduced freely chosen cadence and $\dot{V}O_2$ in young healthy individuals during submaximal cycling. Whether the same apparently advantageous change in pedaling behavior occurs for well-trained cyclists is unknown and is therefore investigated in this study. If it does, strength training could be a way for competitive cyclists to improve movement pattern, cycling economy, and eventually performance.

In the study by Hansen et al. (14), leg strength in itself, freely chosen cadence, and changes in these variables throughout the

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strength training period were not significantly correlated. The researchers suggested that strength training may increase tendon stiffness that potentially might reduce the tendon strain (and thereby tendon organ deformation), afferent feedback, and sensed effort related to a given tendon load. In support, it has recently been shown that patellar tendon cross-sectional area (CSA) was increased after strength training (18,27) and that increased tendon CSA may cause increased tendon stiffness (8). It thus appears possible that strength training may reduce the inhibitory feedback from force-sensitive Golgi tendon organs to the motoneuron pool as previously suggested (1). Such an adaptation in tendons as, for example, the patellar tendon could theoretically cause strength-trained individuals to reduce cadence after strength training without experiencing any increase in afferent feedback, despite the increased pedal force that follows with a reduced cadence. However, Hansen et al. (14) did not measure the effect of strength training on tendon adaptation.

In an attempt to further elucidate the time course and mechanisms of these strength training induced adaptations, both recreationally active individuals and well-trained cyclists performed tests after 4 and 12 weeks of strength training. The main purposes of this study were to investigate the influence of heavy strength training on freely chosen cadence and physiological responses in cyclists and recreationally active individuals and to explore if there is a link between patellar tendon CSA and freely chosen cadence. Based on the literature referred to above, our hypothesis was that strength training would cause both recreationally active individuals and well-trained cyclists to increase their muscle strength and patellar tendon CSA, reduce their freely chosen cadence during submaximal cycling, and consequently reduce physiological responses including $\dot{V}O_2$.

Methods

Experimental Approach to the Problem

To test the hypothesis, the study was designed in the following way: Well-trained cyclists were divided into a strength training group and a control group. The strength training group of cyclists (C-ES) performed heavy strength training in addition to their usual endurance training. The cyclists in the control group (C-E) simply continued their usual endurance training. The recreationally active individuals (R-S) performed the same strength training regimen as that of the C-ES but performed at most one endurance training session per week in addition to the strength training. The intervention was completed during the cyclists' preparation phase before the competition season. Tests of maximal strength and freely chosen cadence at submaximal power output were conducted before the intervention (preintervention), at 4 weeks into the intervention and after the 12-week intervention (postintervention), whereas measurement of patellar tendon CSA was performed before and after the intervention period. Participants were not informed of the hypothesis of the study to not unduly influence their choice of cadence. The participants were instructed to refrain from intense exercise the day preceding a test and to consume the same type of meal before testing. They were not allowed to eat during the last hour preceding a test or to consume coffee or other products containing caffeine during the last 3 hours preceding a test.

Subjects

Twenty-three well-trained cyclists (classified according to the criteria for classification suggested by Jeukendrup et al. [15]) and 9 recreationally active individuals who performed cycling for transportation and recreation volunteered to participate in the study, which was approved by the Southern Norway regional division of the National Committees for Research Ethics. All the participants signed an informed consent form before participation. None of the participants had performed any strength training during the preceding 6 months. Three of the cyclists and 2 of the recreationally active individuals did not complete the study because of illness, and their data are not included. In C-ES, 11 participants completed the study ([all men], age 27 ± 2 years, height 183 ± 2 cm, body mass 76.1 ± 2.8 kg), 9 cyclists in C-E completed the study ([7 men and 2 women], age 30 ± 2 years, height 181 ± 3 cm, body mass 74.9 ± 3.1 kg), and 7 of the participants in R-S completed the study ([all men], age 26 ± 2 years, height 181 ± 3 cm, body mass 75.7 ± 3.4 kg).

Procedures

The participants were instructed to refrain from intense exercise on the day preceding a test, to prepare for the tests as they would have done for a competition, meaning that they should ensure proper hydration status, get enough sleep, and consume the same type of meal before each test. They were not allowed to eat during the hour preceding a test or to consume coffee or other products containing caffeine during the last 3 hours before a test. All tests were performed under similar environmental conditions (20–22°C). The preintervention and postintervention tests were performed at approximately the same time of the day to avoid circadian variance. The subjects were given verbal encouragement throughout the testing of maximal strength and maximal oxygen consumption ($\dot{V}O_2max$) to provide optimal arousal levels. Both preintervention and postintervention tests were organized in 2 separate test sessions on separate days. Maximal strength was tested in the first test session, whereas freely chosen cadence, physiological responses during cycling at this cadence, and $\dot{V}O_2max$ were tested in the second test session. Both cycling tests were performed on the same electromagnetically braked cycle ergometer (Lode Excalibur Sport, Lode B.V., Groningen, The Netherlands), which was adjusted according to each participant's preferences for the seat and handlebar height, horizontal distance between the tip of the seat and bottom bracket, and distance between the seat and the handlebars. The participants were allowed to freely choose the cadence during all cycling tests. They had no visual feedback of the cadence and used

their own cycling shoes and pedals. The participants in R-S borrowed cycling shoes at the laboratory.

Maximal Strength

Maximal strength in leg extensors was measured as 1 repetition maximum (1RM) in half squat. Preintervention and postintervention values for the cyclists have been reported previously (26). Before the preintervention test, 2 familiarization sessions were conducted with the purpose of instructing the participants in proper half squat technique and testing procedure. Strength tests were always preceded by a 10-minute warm-up on a cycle ergometer. After warm-up, the participants performed a standardized protocol consisting of 3 sets with gradually increased loads (40, 75, and 85% of predicted 1RM) and decreased number of repetitions (10, 7, and 3). The depth of the half squat in the 1RM test was set to a knee angle of 90°. Verbal encouragement was given during the test. To ensure similar knee angles during all tests, the participants' squat depth was carefully monitored and marked on a scale on the Smith machine. Each participant had to reach the individual depth marked on the scale for the lift to be accepted. Similarly, the placement of the feet was monitored for each participant to ensure identical test positions during all tests. 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 participant failed to lift the same load after 2–3 consecutive attempts. The rest period between each attempt was 3 minutes. The preinterventions and postintervention tests were conducted using the same equipment with identical positioning of the participant relative to the equipment and monitored by the same investigator. The coefficient of variation for test-retest reliability for this test is found to be 2.9%. The postintervention test for maximal strength was conducted 3–5 days after the last strength training session.

Freely Chosen Cadence and Physiological Response

Freely chosen cadence and physiological response were measured during a 5-minute bout at a power output of 125 W. With the apparently modest power output, we wanted to simulate the workload that competitive road cyclists are exposed to during approximately half of the time in a race (4). During the last 3 minutes of the bout, cadence, $\dot{V}O_2$, and heart rate (HR) were measured and mean values were used for statistical analysis. Freely chosen cadence has been shown to be a robust innate voluntary motor rhythm (13). The $\dot{V}O_2$ was measured using a computerized metabolic system with mixing chamber (Oxycon Pro, Erich Jaeger, Hoechberg, Germany) and 30-second sampling periods. The gas analyzers were calibrated against certified calibration gases of known concentrations before every test. The flow turbine (Triple V, Erich Jaeger, Hoechberg, Germany) was calibrated before every test with a 3 l, 5530 series, calibration syringe (Hans Rudolph, Kansas City, Mo, USA). The HR was measured with an HR monitor (Polar, Kempele, Finland). A blood sample was taken from a fingertip 30 seconds after the end of the 5-minute bout and was analyzed for whole-blood lactate concentration [La^-] using a portable lactate analyzer (Lactate Pro LT-1710, Arcray Inc., Kyoto, Japan). The rate of perceived exertion (RPE) was measured at 4 minutes and 50 seconds into the bout using Borg's 6–20 scale (3). After completion of the submaximal cycling, which was a part of a lactate profile test (data to be reported elsewhere), participants rested for 3 hours before preparing for the $\dot{V}O_2$max test.

Maximal Oxygen Consumption

Before the incremental cycle ergometer test for the determination of $\dot{V}O_2$max, the participants performed a 10-minute warm-up on the cycle ergometer followed by a short rest period. The $\dot{V}O_2$max test was then initiated with 1-minute cycling at a power output corresponding to 3 $W \cdot kg^{-1}$ (rounded down to the nearest 50 W). Power output was subsequently increased by 25 $W \cdot min^{-1}$ until exhaustion. Cadence was freely chosen by participants in this test. When the participants 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 for as long as possible (usually 30–60 seconds). The $\dot{V}O_2$max and the complementary data were calculated as the average of the 2 highest measurements.

Patellar Tendon Cross-Sectional Area

Magnetic resonance tomography (MR) (Magnetom Avanto 1.5 T, Siemens AG, Munich, Germany) was used to measure patellar tendon CSA. The participants were scanned in a supine position with the feet fixed and elevated on a pad. The patellar tendon CSA was measured in the cross section just distal to the patellar insertion by axial plane MR using 1 image with a slice thickness of 5 mm. The images were subsequently uploaded to a computer for further analysis using a tracer function in the software. Because there was no difference in patellar tendon CSA, the mean value of the right and the left was used in the statistical analysis. The coefficient of variation for test-retest reliability for this test is found to be 1.6%.

Training

Endurance training for C-E and C-ES consisted primarily of cycling, but some crosscountry skiing was also performed (up to 10% of total training duration). Endurance training duration was calculated based on recordings from HR monitors (Polar). During the intervention period, C-E and C-ES performed 130 ± 12 and 119 ± 13 hours of endurance training, respectively ($p = 0.57$).

Heavy strength training performed by C-ES and R-S targeted leg strength and was performed twice a week. The heavy strength training was conducted with emphasis on maximal mobilization in the concentric phase (lasting around 1 second), whereas the eccentric and noncycling specific phase was performed more slowly (lasting around 2–3 seconds). On days where both strength and endurance training were scheduled for C-ES, the cyclists were encouraged to perform strength training in the first training session of the day and

Table 1. Results from the $\dot{V}O_2$max test pre and post the 12-week intervention period in which cyclists added heavy strength training to their endurance training (C-ES), recreationally active individuals performed the same strength training program as that of C-ES, but without endurance training (R-S), and cyclists performed their usual endurance training (C-E).*†

	C-ES ($n = 11$)		C-E ($n = 9$)		R-S ($n = 7$)	
	Pre	Post	Pre	Post	Pre	Post
$\dot{V}O_2$max						
($L \cdot min^{-1}$)	5.10 ± 0.17	5.28 ± 0.22‡	5.10 ± 0.33	5.20 ± 0.33‡	4.31 ± 0.15§	4.44 ± 0.12
($ml \cdot kg^{-1} \cdot min^{-1}$)	66.8 ± 1.6	69.0 ± 1.6‡	65.9 ± 2.0	69.8 ± 2.5‡	57.5 ± 2.8§	58.3 ± 2.6
RER	1.10 ± 0.01	1.10 ± 0.01	1.08 ± 0.01	1.07 ± 0.01	1.15 ± 0.02	1.13 ± 0.03
HR_{peak} ($b \cdot min^{-1}$)	188 ± 3	188 ± 3	185 ± 3	184 ± 3	195 ± 3	196 ± 2
Cadence (rpm)	93 ± 3	90 ± 3	95 ± 1	98 ± 3	87 ± 4	82 ± 2

*$\dot{V}O_2$max = maximal oxygen consumption; RER = respiratory exchange ratio; HR_{peak} = peak heart rate; rpm = revolutions per minute; C-ES = endurance training combined with strength training; R-S = Recreationally active individuals; C-E = usual endurance training only.

†Values are mean ± *SE.*

‡Different from preintervention ($p < 0.05$).

§Different from C-ES and C-E at preintervention ($p < 0.05$).

endurance training in the second session. A review of the cyclists' training diaries confirmed that the cyclists largely complied with this guideline.

At the start of each strength training session, the participants performed an approximately 10-minute warm-up at self-selected intensity on a cycle ergometer, followed by 2–3 warm-up sets of half squat with gradually increasing load. The performed strength exercises were half squat, leg press with 1 leg at a time, standing 1-legged hip flexion, and ankle plantar flexion. Both C-ES and R-S were supervised by an investigator at all sessions during the first 2 weeks and thereafter at least once every second week for the remaining part of the intervention period. During the first 3 weeks, the participants trained with 10RM sets in the first session of the week and 6RM sets in the second session. During the next 3 weeks, sets were adjusted to 8RM and 5RM for the first and second weekly sessions, respectively. During the final 6 weeks, sets were adjusted to 6RM and 4RM, respectively. The participants were encouraged to continuously increase their RM loads throughout the intervention period, and assistance was permitted on the last repetition. The number of sets in each exercise was always 3. Adherence to the strength training program was high, with C-ES and R-S completing 97 ± 1 and 92 ± 2% of the prescribed strength training sessions, respectively.

Statistical Analyses

All values presented in the text, figures, and tables are mean ± *SE.* To test for differences between groups at baseline, 1-way analysis of variance (ANOVA) was used. If a significant difference was found, a Tukey's honestly significant difference (HSD) post hoc analysis was performed. For each group, measurements at baseline, after 4 weeks, and after the intervention were compared using 1-way repeated measures ANOVA. If the ANOVA reached significance, a Tukey's HSD test was performed for post hoc analysis. To test for any differences between groups in relative changes, 2-way repeated measures ANOVA (time of intervention period and group as factors) with Bonferroni post hoc tests were performed to evaluate differences. In addition, 2-way repeated measures ANOVA (time of intervention and group as factors) with Bonferroni post hoc tests were performed for the evaluation of

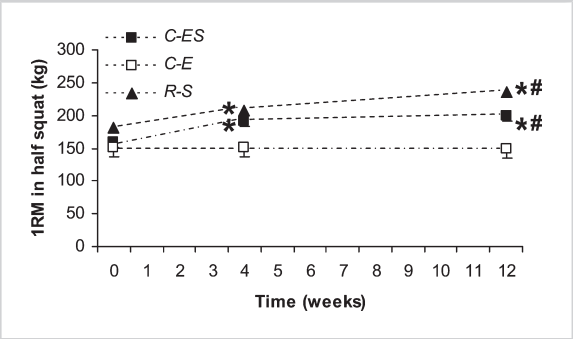

Figure 1. One repetition maximum (1RM) in half squat at preintervention (0 weeks), 4 weeks into the intervention period, and after the 12-week intervention period in which cyclists added heavy strength training to their endurance training (C-ES), recreationally active individuals performed the same strength training program as C-ES but without endurance training (R-S), and acyclists who performed their usual endurance training only (C-E). *Greater than at preintervention ($p < 0.01$). #Different from C-E in relative changes from preintervention to postintervention and different from C-E in absolute values ($p < 0.01$).

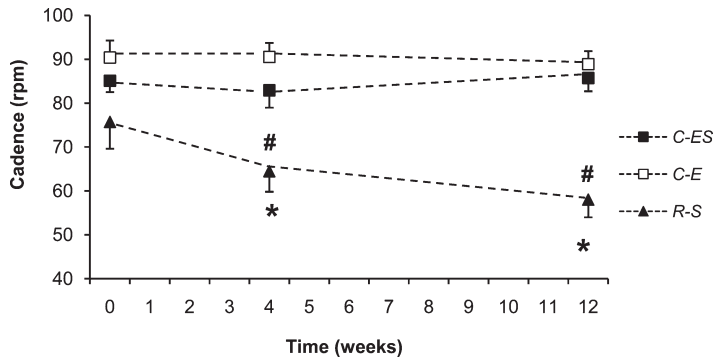

Figure 2. Freely chosen cadence at 125 W at preintervention (0 weeks), 4 weeks into the intervention period, and after the 12-week intervention period in which the cyclists added heavy strength training to their endurance training (C-ES), recreationally active individuals performed the same strength training program as C-ES did, but without endurance training (R-S), and cyclists who performed their usual endurance training only (C-E). *Lower than at preintervention $*p < 0.05$). #Different from C-ES and C-E in relative changes from preintervention and lower absolute values than C-ES and C-E ($p < 0.05$).

differences between groups in absolute values. Preintervention and postintervention measurements of patellar tendon CSA for each group were compared using paired Student's *t*-test, and the groups were compared for differences in relative changes by 1-way ANOVA with Tukey's HSD post hoc analysis. Test-retest reliability (intraclass correlation) for measurement of patellar tendon CSA was 0.98. For measurement of patellar tendon CSA, there was a statistical power of 80% to detect differences within groups of 2.4%, using a significance level (alpha) of 0.05 (2-tailed). The test-retest reliability (intraclass correlation) for measurement of freely chosen cadence was 0.87. For measurement of freely chosen cadence, there was a statistical power of 80% to detect differences within groups of 6.8%, using a significance level (alpha) of 0.05 (2-tailed). Statistical analyses were performed in GraphPad Prism 5.01 (GraphPad Sofware Inc., La Jolla, CA, USA). Correlation analyses (Pearson product-moment correlation coefficient) and Students *t*-tests were performed in Excel 2003 (Microsoft Corporation, Redmond, WA, USA). Analyses of intraclass correlation coefficient were performed in Statistical Package for Social Sciences, Version 16 (Chicago, IL, USA). All analyses resulting in $p \leq 0.05$ were considered statistically significant.

Results

Baseline

Before the intervention period began, some differences between R-S and the 2 groups of cyclists were observed. Thus, $\dot{V}O_2max$ and W_{max} were lower in R-S than in C-ES and C-E ($p < 0.05$, Table 1). In addition, R-S reported a higher RPE and had a higher [La$^-$] than did the 2 groups of cyclists during cycling at 125 W ($p < 0.05$, Figure 4). There were no differences between C-ES and C-E before the intervention period. Furthermore, there were no differences between groups in strength before the intervention period.

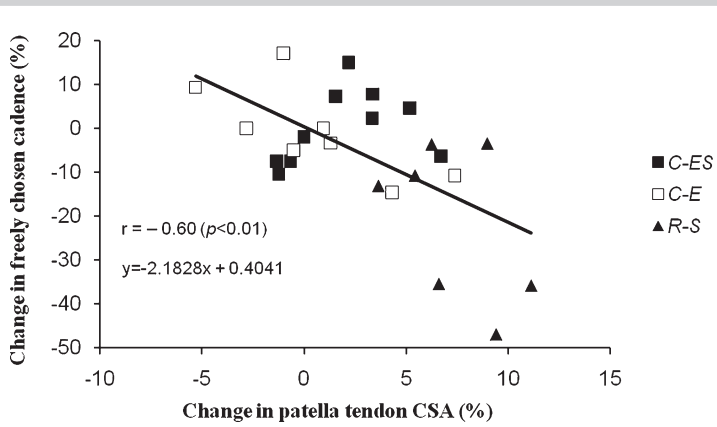

Figure 3. Correlation between change in patellar tendon cross-sectional area (CSA) and freely chosen cadence during cycling at 125 W from before to after the 12-week intervention period. Data are from cyclists who added heavy strength training to their endurance training (C-ES), cyclists who only performed usual endurance training (C-E) and recreationally active individuals who performed the same strength training program as C-ES, but without endurance training (R-S) are included.

Strength

The R-S and C-ES increased 1RM in half squat to a similar extent after 4 weeks of training (15 ± 1 and 16 ± 2%, respectively; $p < 0.01$, Figure 1) and after completion of the entire intervention period (31 ± 3 and 26 ± 2%, respectively; $p < 0.01$, Figure 1). For comparison, strength remained unchanged in C-E.

$\dot{V}O_2max$, Wmax, and Body Mass

There were no significant changes in $\dot{V}O_2max$ and body mass from preintervention to 4 weeks into the intervention

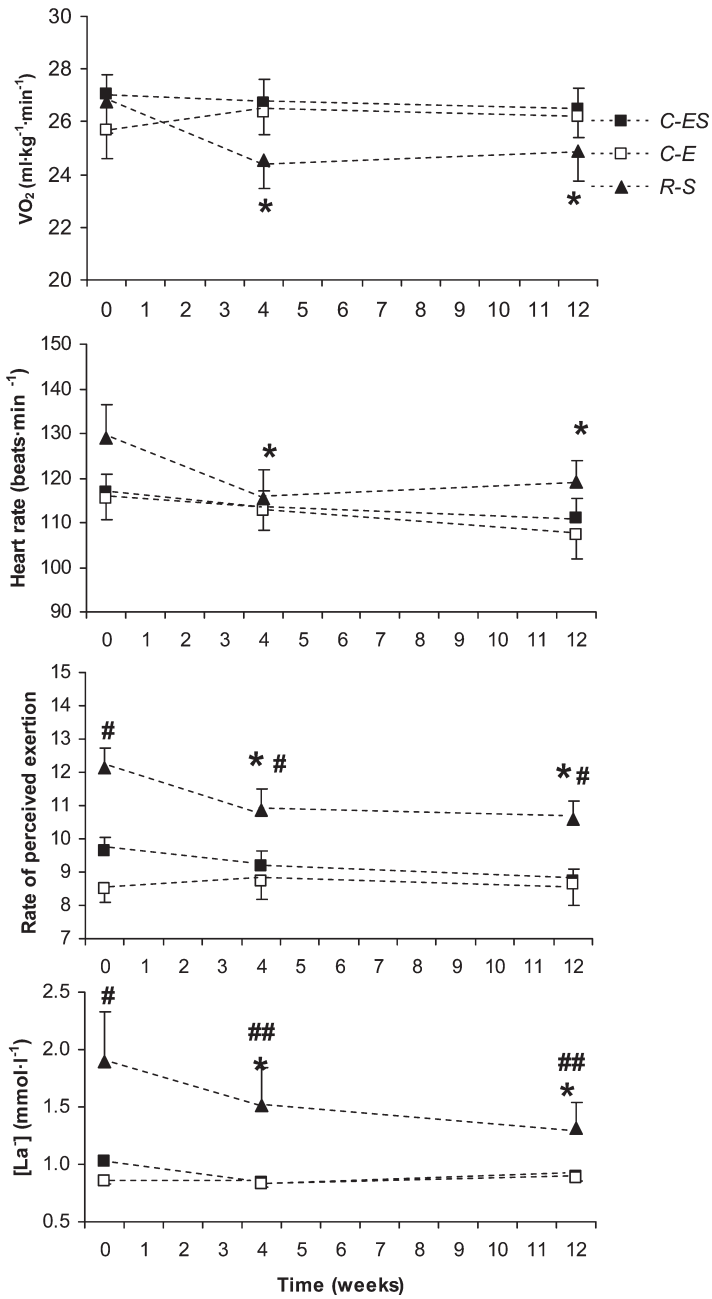

Figure 4. Physiological responses during cycling at freely chosen cadence at 125 W at preintervention (0 weeks), 4 weeks into the intervention period, and after the 12-week intervention period in which cyclists added heavy strength training to their endurance training (C-ES), recreationally active individuals performed the same strength training program as C-ES, but without endurance training (R-S), and cyclists who performed their usual endurance training only (C-E). *Lower than at preintervention ($p \leq 0.05$). #Higher than C-E and C-ES ($p < 0.05$). ##Different from C-E in relative changes from preintervention ($p < 0.05$).

period (data not shown). No significant difference in body mass–adjusted $\dot{V}O_2$max (ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) was observed in R-S from preintervention to postintervention, whereas C-ES and C-E increased $\dot{V}O_2$max by 3 ± 1 and 6 ± 2%, respectively ($p \leq 0.05$). There was no statistically significant difference between C-ES and C-E in relative changes in $\dot{V}O_2$max (Table 1). Body mass increased by 2 ± 2% in R-S from preintervention to postintervention ($p < 0.05$), whereas no significant changes occurred in C-ES and C-E. The ANOVAs revealed no significant differences between groups in relative changes in body mass and $\dot{V}O_2$max, at either 4 weeks or postintervention (data not shown).

Freely Chosen Cadence

Before the intervention started, there were no significant differences between groups in freely chosen cadence (Figure 2). Freely chosen cadence for R-S decreased by 11 ± 5 rpm ($p < 0.05$) from preintervention to 4 weeks into the intervention period and remained at a similar value at postintervention (Figure 2). No significant changes were observed in C-ES and in C-E (Figure 2). Four weeks into the intervention period and at postintervention, cadence was lower in R-S than in C-ES and in C-E ($p < 0.05$). Strength improvement and reduction in freely chosen cadence were not correlated for either R-S or C-ES. There was a correlation between increased CSA of the patellar tendon and reduced freely chosen cadence using data pooled from all 3 groups ($r = -0.60$, $p < 0.01$, Figure 3).

Physiological Responses during Submaximal Cycling at Freely Chosen Cadence

The R-S reduced their $\dot{V}O_2$ (−8 ± 2%), HR (−10 ± 3%), RPE (−10 ± 4%), and [la^-] (−17 ± 5%) during cycling at freely chosen cadence at 125 W at 4 weeks and had a similarly reduced response throughout the intervention period ($p < 0.05$). No significant changes were observed in the other 2 groups (Figure 4). There were

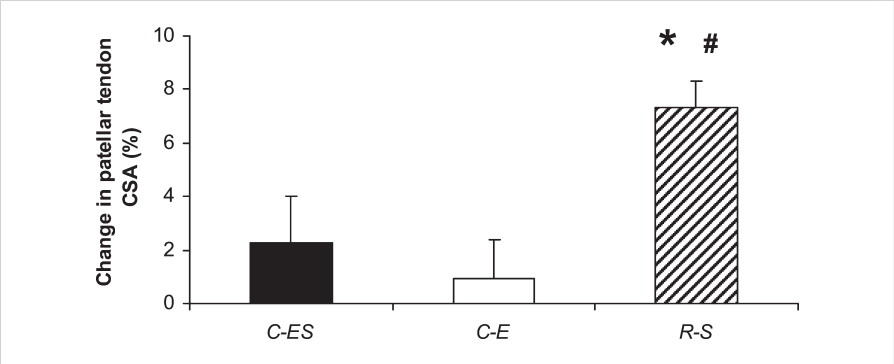

Figure 5. Relative changes in patellar tendon cross-sectional area (CSA) from before to after the intervention period in which cyclists added heavy strength training to their endurance training (C-ES), recreationally active individuals performed the same strength training program as C-ES, but without endurance training (R-S), and cyclists who performed their usual endurance training only (C-E). *Postintervention value is greater than preintervention value ($p < 0.01$). #Different from C-E in relative changes from before to after the intervention ($p < 0.05$).

no significant differences between groups in relative changes in $\dot{V}O_2$, HR, or RPE at either 4 weeks or postintervention. The relative changes in [la^-] were larger in R-S than in C-E at both 4 weeks and postintervention ($p < 0.05$), whereas no significant differences were observed between R-S and C-ES.

Patellar Tendon Cross-Sectional Area

The baseline CSA of the patellar tendon in C-ES, C-E, and R-S was 185 ± 6, 183 ± 7, and 165 ± 5 mm^2, respectively. There was no statistically significant difference between groups. Only R-S increased their patellar tendon CSA (to 177 ± 5 mm^2 postintervention, $p < 0.001$). The relative increase in patellar tendon CSA in R-S was significantly larger than that in C-E (Figure 5, $p < 0.05$).

Discussion

The novel finding of this study was that heavy strength training did not influence the freely chosen cadence of well-trained cyclists. However, another part of the hypothesis was supported, namely, that strength training caused recreationally active individuals to reduce their freely chosen cadence during submaximal cycling. This reduced cadence observed in the recreationally active individuals was accompanied by a reduction in physiological responses to submaximal cycling ($\dot{V}O_2$, HR, RPE, and [la^-]). Furthermore, this study revealed that the reduction in the freely chosen cadence in recreationally active individuals occurred during the early phase of the strength training period, that is, within the first 4 weeks. Another novel finding from this study was that the reduction in the freely chosen cadence may be associated with an increase in patellar tendon CSA, which was only observed in the recreationally active individuals.

The increase in maximal strength for both R-S and C-ES was within the expected magnitude for the present type of training protocol (19), and it was slightly larger than the strength improvement in a similar study (14). The latter finding is probably because the participants in this study had not performed strength training during the 6 months before the intervention, whereas the participants in the study by Hansen et al. (14) had experience with strength training on a recreational basis. In that study, leg strength and freely chosen cadence were not significantly correlated. In addition, changes in these variables across the intervention period were not correlated, a finding corroborated by this study.

This study adds new knowledge about the time aspect of the reduction in freely chosen cadence. A reduction of the cadence was observed already after 4 weeks of strength training. It may be argued that this rapid reduction in cadence is because of a familiarization response in R-S. However, Hansen and Ohnstad (13) investigated this issue in recreational active individuals previously and concluded that freely chosen cadence during submaximal cycling is constant throughout 12 weeks. After 4 weeks, R-S had increased their maximal strength by 15 ± 1%, which is in line with the total strength increase of 12% in leg curl and 20% in squat in the study by Hansen et al. (14). One interpretation of this could be that a sort of threshold of strength improvement is required for changes in pedaling behavior to occur. However, neither the study by Hansen et al. (14) nor this study found a correlation between strength improvement and reduction of the freely chosen cadence. Furthermore, the fact that freely chosen cadence did not decrease for C-ES despite increased strength supports the suggestion that muscle strength per se is apparently not a key factor affecting the choice of cadence.

If muscle strength in itself does not play a key role in freely chosen cadence, then the effects of the strength training on other systems of the body should contribute to the observed reduction of freely chosen cadence. Because the reduction of the freely chosen cadence is observed already 4 weeks into the strength training period and considerable neural adaptations are suggested to occur during this first adaptation phase to strength training (10), nervous system adaptations could contribute to the explanation of the present findings. There is plasticity within the nervous system (10), but knowledge about the precise nature of the neuromuscular responses to strength training and the transfer between adaptations in strength-trained movements to other movements is limited (6). However, strength training may reduce the inhibitory feedback from force-sensitive Golgi tendon organs to the motoneuron pool (1), and this could be because of increased tendon stiffness resulting in less tendon strain.

Strength training has previously been shown to increase the CSA of the patellar tendon (18,27). Furthermore, increased tendon stiffness has been observed after strength training (18,21,27), and it is associated with increased tendon CSA (8,18). As proposed by Hansen et al. (14), increased tendon CSA and stiffness because of strength training could reduce tendon strain at a certain loading and, consequently, reduce the afferent feedback from mechanoreceptors, eventually influencing sensed effort. That again could stimulate participants to change their motor behavior by decreasing their freely chosen cadence, despite the resultant increase in the force in each pedal thrust (11,28). This idea is supported by the finding of increased patellar tendon CSA and reduced cadence in R-S, although no such statistically significant changes were found in C-ES and C-E. Although it is important to bear in mind the relatively low number of participants when the results of this study are interpreted, there was a negative correlation between increment of patellar tendon CSA and reduction in freely chosen cadence using pooled data from all 3 groups. It is possible that some factors being unrelated with tendon characteristics, but in another way associated with the motor control of pedaling and linked with hours of weekly cycle training, cause well-trained cyclists' cadence to be robust and apparently unaffected by the intervention of heavy strength training. It is also possible that well-trained cyclists, because of natural selection, represent individuals with some special neuromuscular characteristics. This is something that perhaps also can explain why it is sometimes observed that trained cyclists pedal faster than more inexperienced cyclists do. In this study, only proximal patellar tendon CSA was measured because of the findings of largest change of CSA in this region of the patellar tendon after strength training (18). Unfortunately, we did not measure patellar tendon CSA at 4 weeks when a reduced freely chosen cadence among participants of R-S was first observed, so we do not know whether adaptations in the tendon had occurred already at that time point. However, there has been reported elevated collagen synthesis response in the patellar tendon after a single loading bout (16,23), and albeit speculative, changes in patellar properties could occur after 4 weeks of strength training. Indeed, both isometric training and plyometric training have been shown to increase tendon stiffness already after 6 weeks (5).

The finding of an approximately 7% increase in patellar tendon CSA is in accordance with other studies finding 5–7% increases in CSA in the same region of the patellar tendon after 9–12 weeks of strength and explosive training in untrained individuals (18,27). That no significant increase in patellar tendon CSA was found for C-ES in this study may be related to the relatively large volume of concurrent endurance training performed by the cyclists. Impaired strength training adaptations have previously been observed when strength training is combined with endurance training (20,25). We may then hypothesize that C-ES achieved a smaller adaptation in the patellar tendon CSA because of inhibitory effects of the concurrent endurance training. On the other side, at baseline, C-ES and C-E tended to have a larger patellar tendon CSA than R-S did ($p = 0.12$ and $p = 0.15$, respectively), and when we pooled both groups of cyclists and compared them with R-S, the cyclists had a larger patellar tendon CSA at baseline ($p = 0.03$). This observation implies that some adaptations in the patellar tendon of the cyclists had already taken place as a result of a large volume of cycling over several years. The observation of no change in patellar tendon CSA in C-ES could thus also be explained by the hypothesis that the cyclists had reached their maximal potential of tendon hypertrophy.

The reduction in the freely chosen cadence after a period of strength training seems to explain the reduced physiological responses at submaximal cycling for individuals in R-S. For comparison, cycling economy at submaximal power output was not changed for any of the cyclist groups. The $\dot{V}O_2$max of the cyclists was increased at the postintervention test as a consequence of the endurance training performed. Interestingly, although an inverse relationship between $\dot{V}O_2$max and cycling economy in world class cyclists has been observed (22), this study found that an increase in $\dot{V}O_2$max in well-trained cyclists did not affect cycling economy. It is also worth emphasizing that the added strength training in this study had no negative effects on any of the measurements during submaximal cycling. On the contrary, increased leg strength can improve performance during intensive cycling performed subsequent to prolonged submaximal cycling (26).

In conclusion, freely chosen cadence during submaximal cycling was reduced after a period of heavy strength training in recreationally active individuals but not in well-trained cyclists. The reduced cadence observed in the recreationally active individuals was accompanied by a reduction in physiological responses, including $\dot{V}O_2$, HR, RPE, and [la^-]. The reduction in freely chosen cadence may partly be accounted for by a concurrently observed increase of tendon CSA, which possibly increases tendon stiffness and thereby reduces tendon strain, afferent feedback, and eventually changes motor behavior. Finally, this study showed that the reduction in the freely chosen cadence in recreationally active individuals occurred during the early adaptation phase to strength training, that is, within the first 4 weeks.

Practical Applications

In this study, heavy strength training affected recreationally active individuals to reduce their freely chosen cadence during submaximal cycling. This changed rhythmic movement behavior was accompanied by a reduced physiological response being a consequence of the circumstance that freely chosen cadence in the starting point is high and energetically nonoptimal compared with a lower cadence. In other words, this study suggests that strength training affects the freely chosen pedal cadence in recreationally active individuals, leading them to choose a lower and more energetically

optimal cadence. The same was not seen for well-trained cyclists. Thus, enhanced performance in well-trained cyclists after strength training should be explained by other factors than the choice of more energetically optimal cadence.

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