On modern multigeared bicycles, the cyclist is free to choose any available gear ratio to achieve a target cycling velocity. The choice of the gear ratio at a given cycling velocity in turn determines the cadence. Thus, as noted by Vercruyssen and Brisswalter,1 the cadence is one of the only variables that an athlete can modify during cycling exercise to optimize performance. Hence, cadence selection has been of interest since the multi-geared chain-driven bicycle was invented in the late 19th century. For more than 100 years, cyclists, coaches, and researchers have debated over cadence choice. Even in the last 10 years, several scientific studies on the freely chosen cadence (FCC) have been published, further demonstrating that there is a continuous discussion on the theory and practice of cycling. Research has shown that FCC is a highly individual characteristic and is affected by several “external” factors.2 It has been reported that external power output (P_{ext}),3 road gradient,4 crank inertial load,5 drafting,6 training,7 muscle-fiber-type composition,8 and circadian rhythm9 influence FCC. Despite this intense discussion, the underlying factors leading to the choice of a particular cadence are still a subject of debate. Theoretically, cyclists should choose an “optimal cadence” at which relevant physiological and/or biomechanical variables are optimized. However, several studies document the multitude of definitions for “optimal cadence” in cycling (for a review see, eg, Marais and Pelayo10). The term optimal cadence has been defined as the cadence with the lowest EMG activity for a given P_{ext},11 the cadence that minimizes the summed joint moments,12 the cadence that produces the lowest neuromuscular fatigue,13 the cadence with the highest P_{ext} at a specific performance level,14 and the most efficient cadence for energy expenditure.15 The “cadence paradox,”16 which states that competitive cyclists and trained subjects choose a higher cadence than the most efficient cadence (C_{eff}), has been an especially interesting topic in the past.17

Of most interest (at least for a competitive road cyclist) is the cadence that produces the best performance to win a race, not C_{eff}. Therefore, the optimal cadence (C_{opt}) is defined here as the cadence that corresponds to the apex of the P_{ext}–cadence relationship (P_{max}) at a performance level that can be sustained for the given task.14 From a theoretical perspective, cyclists should choose a cadence near C_{opt} to maximize P_{ext} for the given task or to minimize peripheral fatigue at a given P_{ext}. Results from previous studies showed that both FCC and C_{opt} were significantly lower during uphill cycling than during cycling on level ground with the same body position. Taken together, these results suggest that both FCC and C_{opt} are affected in a similar way by road incline, but no
study has addressed whether the difference between FCC and Copt is the same independent of road incline. Moreover, to the best of our knowledge, no study has compared FCC and Copt at a submaximal performance level.

A study by Emanuele and Denoth\(^{18}\) showed that the road incline not only decreased Copt but also decreased \(P_{\text{max}}\). In addition, that study showed that the change in body position from a dropped posture (DP) with the cyclist’s hands on the handlebars and arms fully extended to an upright posture (UP) with the cyclist’s hands on the top portion of the handlebars and arms fully extended significantly increased \(P_{\text{max}}\) without affecting the corresponding Copt. These results led to the conclusion that Copt and FCC should be lower and \(P_{\text{max}}\) should be higher for uphill cycling with UP than for level-ground cycling with DP.\(^{18}\) However, the influence of a simultaneous change in road incline and body position as seen in field observations of cyclists has not been analyzed in an experimental study.

The main aim of this study was to compare FCC and Copt at an endurance-performance level that can be sustained for approximately 1 hour. The hypothesis was that at a performance level corresponding to the maximal lactate steady state (MLSS), experienced cyclists would choose an adequate cadence close to Copt independent of the cycling condition. The second aim of this study was to examine the effect of a concomitant change in road incline and body position on FCC, Copt, and \(P_{\text{max}}\) at an endurance-performance level corresponding to MLSS. The hypothesis was that FCC and Copt would be lower and \(P_{\text{max}}\) higher during uphill cycling with UP than during level-ground cycling with DP.

**Methods**

**Subjects**

Seven well-trained male amateur cyclists (31 ± 6 y, 182.0 ± 4.5 cm, 71.7 ± 6.7 kg) who have competed at the national level volunteered to participate in this study. They were all informed of the nature of this study, as well as the potential risk and discomfort associated with the experimental procedures, before they gave their written consent to participate. The ethical committee of ETH Zurich approved the experimental design.

**Experimental Design**

The subjects were asked to attend 3 test sessions within a 3-week period with at least 2 days between single test days. To improve the reliability of the measurements, the participants were asked to control a number of variables; for the details see Emanuele and Denoth.\(^{14,18}\) The purpose of the first test session was to determine individual FCC and estimate the individual \(P_{\text{ext}}\) at maximal lactate steady state (PM\textsubscript{MLSS}). The purpose of the second and third test sessions was to estimate Copt and \(P_{\text{max}}\) at MLSS when cycling on level ground with DP and when cycling uphill with UP, respectively.

**Determination of FCC.** To determine FCC during level-ground cycling (FCC\textsubscript{LGO}), the subjects cycled with DP at a road inclination of 0% and a speed of 30.2 km/h. During this test, the cyclists were encouraged to change gears and use the gear that felt the most comfortable. However, because of the limited gear ratios, there were limitations on the FCCs. Only the following cadences could be chosen: 60, 65, 70, 75, 80, 85, 90, 95, 100, and 105 rpm. After a 10-minute warm-up at 100 W, \(P_{\text{ext}}\) was increased until it reached a level that the cyclist thought he could maintain for approximately 1 hour. This subjective estimation of PM\textsubscript{MLSS} was reached within 5 to 7 minutes. \(P_{\text{ext}}\) and gear were then held constant for 1 minute, and the cadence (FCC) and \(P_{\text{ext}}\) were recorded. The subjects were then given a 20-minute rest period.

To determine FCC during uphill cycling (FCC\textsubscript{UH}), the same protocol was used, except that subjects cycled with UP on the treadmill with an inclination of 7% and a speed of 15.1 km/h.

**Lactate Minimum Test.** The determination of the lactate minimum power output (PM\textsubscript{M}) using a lactate minimum test (LMT) is a reliable and valid method to predict PM\textsubscript{MLSS} and therefore a good predictor of the specific endurance performance level that can be sustained for approximately 1 hour.\(^{19,20}\) During the LMT, the participants cycled with UP and a constant cadence of 80 rpm, which corresponds to the mean Copt measured by Emanuele and Denoth\(^{18}\) during cycling using an ergometer. The method used to determine PM\textsubscript{M} was based on Fontana et al\(^{21}\) (Figure 1). Briefly, the LMT consisted of 2 incremental tests. The first incremental test started at 100 W and increased 50 W every minute until exhaustion to induce lactic acidosis, followed by 1 minute at 100 W and 7 minutes of complete rest (part 1). After the rest period, a second incremental test started at 100 W with an increase of 25 W every 90 seconds (part 2). During the LMT, heart rate, oxygen uptake, carbon dioxide output, minute ventilation, and breathing frequency were continuously recorded. Blood lactate concentration (bLa) was measured at rest, at exhaustion in part 1, during recovery in part 1 (after 2, 4,
and 7.5 min), and at the end of each stage in part 2. The bLa levels during part 2 of the LMT were plotted against power output, and a third-order polynomial curve was fitted through these data points. The PLM corresponds to the “lactate minimum” in this polynomial curve. PLM was used as an estimation of PMLSS at 80 rpm, the exercise intensity needed for the second and third test sessions.

**Determination of Copt.** To determine Copt at MLSS during uphill cycling, the subjects performed 3 incremental exercise tests at the following 3 cadences: FCC_UH – 10 rpm, FCC_UH, and FCC_UH + 10 rpm in a randomized order. During these tests, the subjects cycled with UP on the treadmill at an 7% inclination at 15.1 km/h. At each cadence, a 2-minute warm up at 100 W was followed by an incremental exercise test comprising 4 increments in Pext (Figure 2): P80MLSS – 20 W (3 min), P80MLSS – 10 W (3 min), P80MLSS (2 min), and P80MLSS + 10 W (2 min). The incremental test was followed by a 2.5-minute cooldown at 100 W. Between the 3 incremental exercise tests, the subjects were given a 14-minute rest to prevent fatigue. bLa was measured at the beginning of the warm-ups and at the end of each stage of the incremental exercise tests. To determine Copt at MLSS, the increase in bLa was analyzed. The increase in bLa from rest until the end of the exercise test was plotted against the cadence used (Figure 3[a]). A second-order polynomial-regression line was fitted through these data points to determine the bLa–cadence relationship. Copt at MLSS corresponds to the “lactate minimum” in this polynomial curve. A quadratic curve constrained to pass through the origin was then fit to Copt at MLSS and PMLSS at 80 rpm to assess the individual Pmax at MLSS (Figure 3[b]).

To determine Copt at MLSS during level-ground cycling, the same protocol was used, except that the treadmill was set at an inclination of 0%, the speed was increased to 30.2 km/h, and the participants cycled with DP. The bLa–cadence relationship for level-ground cycling was then compared with the bLa–cadence relationship for uphill cycling. Pmax for uphill cycling with UP corresponding to the intersection point of the 2 bLa–cadence relationships was used to fit a quadratic curve constrained to pass through the origin to assess the individual Pmax at MLSS for level-ground cycling with DP.

**Equipment**

In all tests, the subjects exercised on a normal road-racing bicycle with 24-36-48 teeth chain rings and 12-13-14-15-17-18-19-20-21-24 teeth cog set. The bicycle was adjusted so that the vertical and horizontal positions of the saddle and the handlebar related to the crank axis matched each subject’s own bicycle. The racing bicycle was equipped with a standard crank (length = 170 mm), clipless pedals, and a professional (8 strain gages) SRM PowerMeter (Schroerer Rad Messtechnik, Jülich, Germany). Using the SRM PowerMeter, Pext, cadence, and heart rate were recorded. During all tests except the LMT, the bicycle was mounted on a treadmill (Woodway, Weil...
am Rhein, Germany). Thereby, the bicycle was fixed with the fork to a sliding carriage, which allowed a horizontal bicycle translation relative to the laboratory (Figure 4). \( P_{ext} \) was adjusted by changing the mass of a weight magazine. This magazine was connected to a wire that ran over a pulley placed behind the treadmill and was then tied to the back of the bicycle. The mass needed to achieve the target \( P_{ext} \) was calculated for each subject based on his measured \( P_{ext} \) without the weight magazine.

During the LMT, the bicycle was mounted on an indoor trainer (Flow, Tacx, Wassenaar, Netherlands). The gas-exchange and ventilatory variables were measured breath by breath with an Oxycon Mobile device (Viasys Healthcare, Höchberg, Germany). The lactate concentration in the blood samples (20 \( \mu \)L) taken from the earlobes was analyzed with a Biosen C-Line analyzer (EKF Industrie-Elektronik, Barleben, Germany).

### Statistics

All of the statistical analyses were performed using SPSS Statistics 17 (SPSS Inc, Chicago, IL). The level of significance was set at \( P < .05 \). Based on the estimated coefficient of variation for the measured bLa of 5%, the 95% confidence interval (CI) for assessing the individual \( C_{opt} \) at MLSS (Figure 5) was calculated using the model-based residual bootstrapping method for regression. Assuming that the cyclists use the next higher \( (C_{opt}^+ + 5 \text{ rpm}) \) or lower \( (C_{opt}^- – 5 \text{ rpm}) \) possible cadence to the real \( C_{opt} \), the theoretical 95% CI for the difference between FCC and \( C_{opt} \) at MLSS \( (\Delta C) \) was calculated using the 95% CI for the individual \( C_{opt} \) at MLSS and the available gear ratios. The theoretical 95% CIs for \( \Delta C \) were also calculated assuming that the cyclists chose \( C_{opt}^+ + 5 \text{ rpm} \) or \( C_{opt}^- – 5 \text{ rpm} \). The statistical power for detecting a relevant \( \Delta C \) over 5 rpm was calculated for a sample size of 7. All the parameter values were compared using the Student paired \( t \) test. The variables were summarized with descriptive statistics (mean ± SD).

### Results

Based on the coefficient of variation for the measured increase in bLa, the residual bootstrap yielded a 95% CI for assessment of the individual \( C_{opt} \) at MLSS of 4.8 rpm (Figure 6[a]). Assuming that the cyclists use \( C_{opt}^+ \) or \( C_{opt}^- \), the theoretical 95% CI for \( \Delta C \) was 0 ± 7.4 rpm (Figure 6[b]). During level-ground cycling, \( \Delta C \) of all cyclists was within this CI, and during uphill cycling the difference of 1 cyclist was outside this CI. Assuming that the cyclists use \( C_{opt}^+ + 5 \text{ rpm} \) or \( C_{opt}^- – 5 \text{ rpm} \), the theoretical 95% CIs for \( \Delta C \) were 7.5 ± 3.7 rpm and –7.5 ± 3.7 rpm. During level-ground cycling, \( \Delta C \) of 6 cyclists was outside this CI, and during uphill cycling, \( \Delta C \) of 4 cyclists was outside this CI. Thus, during level-ground cycling, 6 cyclists used \( C_{opt}^+ + 5 \text{ rpm} \) or \( C_{opt}^- – 5 \text{ rpm} \), 1 cyclist used \( C_{opt}^+ \) or \( C_{opt}^- – 5 \text{ rpm} \), and 1 cyclist used \( C_{opt}^+ + 5 \text{ rpm} \).

For uphill cycling with UP and level-ground cycling with DP, the determined FCC and \( C_{opt} \) at MLSS were not significantly different. The statistical power to detect a relevant difference of 5 rpm between FCC and \( C_{opt} \) at MLSS was .84 for a sample size of 7.

FCC at the subjective self-selected \( P_{MLSS} \) (278 ± 30 W) was significantly lower \( (P < .05) \) when cycling uphill with UP (82.1 ± 11.1 rpm) than when cycling on level ground with UP (89.3 ± 10.6 rpm). \( P_{MLSS} \) at 80 rpm estimated using the LMT was 261 ± 24 W. The assessed individual \( C_{opt} \) at MLSS was significantly higher \( (P < .01) \) for level-ground cycling with UP (87.7 ± 10.9 rpm) than for uphill cycling with UP (81.5 ± 9.8 rpm). \( C_{opt} \) at MLSS for level-ground cycling was 7.5% ± 2.3% higher than for uphill cycling. Finally, \( P_{max} \) at MLSS was significantly higher \( (2.0\% ± 2.1\% ; P < .05) \) for uphill cycling with UP than for level-ground cycling with DP (Figure 3[b]).
The main purpose of this study was to compare FCC and Copt at an endurance-performance level that corresponded to MLSS. The hypothesis was that experienced cyclists would choose an adequate cadence close to Copt independent of the cycling condition. The results revealed that most but not all experienced cyclists choose the next higher (Copt+) or the next lower (Copt–) possible cadence to Copt, independent of the cycling condition. However, the results also showed that, independent of road incline and body position, FCC and Copt at MLSS were not significantly different. Here it must be stated that the statistical power to detect a difference between FCC and Copt at MLSS was greater than .8 only for an assumed difference of 5 rpm between FCC and Copt at MLSS. On the other hand, a difference between FCC and Copt at MLSS of less than 5 rpm is not relevant from a performance-related point of view, because such a difference reduces $P_{ext}$ less than 0.5%. Furthermore, most of the individual differences between FCC and Copt at MLSS can be attributed to the discrete available gear ratios and the precision in determination of Copt at MLSS.

According to Emanuele and Denoth Copt is defined as the cadence that corresponds to the apex of the $P_{ext}$–cadence relationship at a specific performance level, for example, at a fixed bLa. From a theoretical perspective, Copt can be indirectly assessed by measuring different variables at a constant $P_{ext}$ while manipulating the cadence. One of these indicative variables is bLa. Emanuele and Denoth showed that to assess Copt at a fixed bLa, the $P_{ext}$–cadence relationship can be fitted using a quadratic-regression line that is constrained to pass through the origin. This result implies that Copt can also be assessed using a quadratic bLa–cadence relationship at a constant $P_{ext}$. Thus, the results from this study confirm the assumption that most competitive cyclists choose a cadence near Copt to minimize peripheral fatigue at a given $P_{ext}$ or to maximize $P_{ext}$ for the given task. This assumption has been stated by different authors but has never been experimentally demonstrated. The following additional indicative variables for Copt at a constant $P_{ext}$ have been analyzed previously: neuromuscular fatigue, EMG activity, and time to exhaustion. All of the single data sets of these studies were well fitted with a second-order polynomial-regression curve to assess Copt. However, none of these studies assessed Copt and compared it with FCC. Thus, this is the first study to show that most competitive cyclists choose an adequate cadence close to the individual Copt at a specific endurance-performance level. Furthermore, the comparison between level-ground cycling with DP and uphill cycling with UP revealed that not only interindividual differences in FCC but also intraindividual differences in FCC are related to Copt. These are experimental indications of a causative relationship between FCC and Copt. This relationship can also be deduced from the observation that both FCC and Copt decrease.
with increasing fatigue. Thus, the cadence paradox is resolved because most competitive cyclists choose a cadence near \( C_{\text{opt}} \), which is clearly a higher cadence than the most efficient cadence. Kohler and Boutellier have already explained that FCC exceeds Ceff. In their theoretical study, they concluded that FCC is not fixed but depends on the duration of the race and ranges between \( C_{\text{opt}} \) and Ceff. However, in their conclusion they neglected the fact that not only FCC but also \( C_{\text{opt}} \) and Ceff depend on performance level or, rather, race duration.7,14,26 Even their own calculation showed that \( C_{\text{opt}} \), Ceff, and the difference between these cadences depend on performance level or, rather, on type II fiber recruitment. Thus, a change in the difference between Ceff and FCC can be explained by the change in the difference between \( C_{\text{opt}} \) and Ceff. Other studies have tried to explain the cadence paradox have shown a reduced difference between FCC and Ceff with fatigue.6,17,27 Argentin et al,27 for example, showed a significant shift in FCC (87–68 rpm) toward Ceff (65 rpm) after 2 hours of cycling at 65% of maximal aerobic power. As \( C_{\text{opt}} \) decreases with fatigue, which is primarily from an increase in the internal power,14 the reduced difference between FCC and Ceff with fatigue can also be explained by the reduced difference between \( C_{\text{opt}} \) and Ceff with fatigue. Regrettably, no study has simultaneously analyzed the influence of fatigue on FCC, \( C_{\text{opt}} \), and Ceff to confirm this theoretical assumption.

The hypothesis that most competitive cyclists choose a cadence near \( C_{\text{opt}} \) should be confirmed in future studies by simultaneously analyzing the influence of other "external" factors on FCC and \( C_{\text{opt}} \). The factors of interest could include \( P_{\text{ext}} \), fatigue, training, muscle-fiber-type composition, saddle height, and crank length. Furthermore, it is not assumed that all competitive cyclists chose an optimal cadence. Therefore, the percentage of cyclists that chose too high or too low a cadence must be estimated in a future study using a large number of subjects. Studies should also be performed with recreational cyclists and noncyclists to show if the subjects choose an optimal cadence independent of cycling experience. It is recommended that future studies be performed with more cadences tested to enhance precision in determining \( C_{\text{opt}} \).

**Level Ground Versus Uphill**

By comparing level-ground cycling with DP and uphill cycling with UP, this study had a second aim: to determine the influence of a concomitant change in road gradient and body position on FCC, \( P_{\text{max}} \), and \( C_{\text{opt}} \). Concerning FCC, experimental studies have revealed that it is influenced by road gradient but not by body position.28 Thus, a concomitant change in the road gradient and body position should theoretically have the same influence on FCC as only a change of road gradient. Our results on the treadmill support the results from Hansen et al., who also observed a lower FCC when subjects cycled uphill on a treadmill (69 rpm at 150 W and 73 rpm at 250 W) than while cycling on level ground (75 rpm at 150 W and 82 rpm at 250 W). These results also agree with observations of cyclists during their normal training or during competitions.30 A previous study showed that a change in the road gradient (0 vs 7%) alone influences \( P_{\text{max}} \) and \( C_{\text{opt}} \) and that a change in body position (DP vs UP) alone influences \( P_{\text{max}} \) but not \( C_{\text{opt}} \).16 These results led to the assumption that \( C_{\text{opt}} \) is lower and \( P_{\text{max}} \) is higher for uphill cycling with UP than for level-ground cycling with DP. This assumption has now been experimentally confirmed.

**Practical Applications**

The results from this study suggest that most competitive cyclists freely choose a cadence near \( C_{\text{opt}} \) to minimize fatigue at a given \( P_{\text{ext}} \). Thus, athletes should not attempt to copy the cadence used by successful cyclists and coaches should avoid forcing athletes to use a desired cadence. On the other hand, some cyclists freely choose too high or too low a cadence. Thus, the comparison of the individual FCC and the individual \( C_{\text{opt}} \) at a specific endurance-performance level is an adequate method to optimize performance.

The results from the second part of this study confirmed that under real cycling conditions it is advantageous from a performance-related point of view to use a lower cadence and a more upright body position during uphill cycling.

**Conclusion**

Despite the intense discussion on the FCC in cycling, the underlying factors that lead cyclists to choose a particular cadence remained under debate. This study demonstrated that interindividual, as well as intraindividual, differences in FCC are related to differences in \( C_{\text{opt}} \). These results indicate a causal relationship between FCC and \( C_{\text{opt}} \). As expected from a theoretical perspective, most cyclists freely choose a cadence near \( C_{\text{opt}} \) to minimize peripheral fatigue at a given \( P_{\text{ext}} \) or to maximize \( P_{\text{ext}} \) for a given task. Thus, the cadence paradox, which states that competitive cyclists choose a higher cadence than \( C_{\text{eff}} \), has been resolved.

Furthermore, by comparing level-ground cycling with DP and uphill cycling with UP, this study confirmed that under real cycling conditions it is advantageous to use a lower cadence and a more upright body position during uphill cycling.

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