Fatigue during Maximal Sprint Cycling: Unique Role of Cumulative Contraction Cycles

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ABSTRACT

TOMAS, A., E. Z. ROSS, and J. C. MARTIN. Fatigue during Maximal Sprint Cycling: Unique Role of Cumulative Contraction Cycles. *Med. Sci. Sports Exerc.*, Vol. 42, No. 7, pp. 1364–1369, 2010. **Abstract**: Maximal cycling power has been reported to decrease more rapidly when performed with increased pedaling rates. Increasing pedaling rate imposes two constraints on the neuromuscular system: 1) decreased time for muscle excitation and relaxation and 2) increased muscle shortening velocity. Using two crank lengths allows the effects of time and shortening velocity to be evaluated separately. **Purposes**: We conducted this investigation to determine whether the time available for excitation and relaxation or the muscle shortening velocity was mainly responsible for the increased rate of fatigue previously observed with increased pedaling rates and to evaluate the influence of other possible fatiguing constraints. **Methods**: Seven trained cyclists performed 30-s maximal isokinetic cycling trials using two crank lengths: 120 and 220 mm. Pedaling rate was optimized for maximum power for each crank length: 135 rpm for the 120-mm cranks (1.7 $m \cdot s^{-1}$ pedal speed) and 109 rpm for the 220-mm cranks (2.5 $m \cdot s^{-1}$ pedal speed). Power was recorded with an SRM power meter. **Results**: Crank length did not affect peak power: 999 ± 276 W for the 120-mm crank versus 1001 ± 289 W for the 220-mm crank. Fatigue index was greater (58.6% ± 3.7% vs 52.4% ± 4.8%, $P < 0.01$), and total work was less (20.0 ± 1.8 vs 21.4 ± 2.0 kJ, $P < 0.01$) with the higher pedaling rate–shorter crank condition. Regression analyses indicated that the power for the two conditions was most highly related to cumulative work ($r^2 = 0.94$) and to cumulative cycles ($r^2 = 0.99$). **Conclusions**: These results support previous findings and confirm that pedaling rate, rather than pedal speed, was the main factor influencing fatigue. Our novel result was that power decreased by a similar increment with each crank revolution for the two conditions, indicating that each maximal muscular contraction induced a similar amount of fatigue. **Key Words:** POWER, ERGOMETER, MUSCLE, CALCIUM, FORCE

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Several previous investigators have studied exercise-induced reductions in muscular power using maximal cycling protocols. In some fatiguing protocols, pedaling rate varied within the trial (2), and thus, interpretation of fatigue may be complicated by the effects of the power–pedaling rate relationship (10). However, some investigators have studied fatigue using maximal isokinetic cycling (3,13,21). McCartney et al. (21) reported that both peak power and rate of fatigue increased with increasing pedaling rate during 30-s maximal trials at pedaling rates of 60, 100, and 140 rpm. Similarly, Beelen and Sargeant (3) reported that maximum power, total work, and fatigue were significantly greater at 120 rpm than at 60 rpm.

These isokinetic cycling studies demonstrated that fatigue proceeded more rapidly at greater pedaling rates and raised two additional questions. First, was the greater fatigue observed at increased pedaling rates influenced by greater initial peak power? This is an important question because, in previous studies (3,21), initial power was greater at greater pedaling rates, and this difference may have increased the accumulation of metabolic by-products that could have contributed to more rapid fatigue. Second, was increased fatigue associated with pedaling rate *per se* or with linear pedal speed? Pedaling rate limits the time available for muscle excitation and relaxation (6), and thus, any fatigue-related changes in rates of excitation or relaxation (8) would elicit greater fatigue with increasing pedaling rate. Pedal speed (crank length × crank angular velocity), on the other hand, is related to muscle shortening velocity (27). Consequently, fatigue mechanisms that alter force–velocity relationships by decreasing maximum shortening velocity (7) would reduce power to a greater extent with increases in pedal speed. This issue of pedaling rate versus pedal speed cannot be resolved with data from a single crank length because pedaling rate and pedal speed are linearly coupled for any given crank length.

The effects of pedaling rate and pedal speed can be separated by using a range of crank lengths. Martin and

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Spirduso (20) determined maximal power–pedaling rate and maximal power–pedal speed relationships with crank lengths ranging from 120 to 220 mm. They reported that optimal pedaling rate for power production decreased with increasing crank length, whereas optimal pedal speed increased with increasing crank length. These opposite effects of crank length on optimal pedaling rate and optimal pedal speed provide a means to separate the fatiguing effects of pedaling rate from those of pedal speed. Therefore, our primary purpose for conducting this investigation was to determine whether pedaling rate or pedal speed was mainly responsible for the increased rate of fatigue previously observed at greater pedaling rates. We hypothesized that fatigue would proceed more rapidly with the higher pedaling rate–shorter crank condition. Further, our study design involved two pedaling rates and two pedal speeds and allowed us to perform exploratory analyses that could help clarify the cumulative effects of pedaling rate (number of cycles), pedal speed (total arc length described by the pedal), and initial power (cumulative work). Therefore, our secondary purpose was to determine the extent to which fatigue was related to these cumulative variables. We hypothesized that fatigue would be highly related to cumulative work (as a mechanical predictor of metabolic stress) and to the number of cumulative cycles (the cumulative number of maximal contractions).

METHODS

Procedures used in this investigation were reviewed and approved by the institutional review board of the University of Utah. The protocol and procedures were explained verbally, and the participants provided written informed consent before testing. Six male (183.5 ± 7.3 cm, 73.3 ± 3.3 kg) and one female (170.0 cm, 51.2 kg) trained cyclists participated in this study. Trained cyclists were recruited because they are known to be capable of producing stable and reliable values for maximum power (16). Of the seven participants, four were Cycling USA category 2 or 3 amateur road cyclists, one was an expert category off-road cyclist, one was a top-level triathlete, and one was a highly trained recreational cyclist with laboratory protocol experience. The triathlete and the racing cyclists were tested within their competitive season. The participants refrained from intense training the day before each data collection session but otherwise followed their regular training programs.

Participants reported to the laboratory for a total of four sessions. The first and third sessions were for familiarization and included 20 min of cycling with the novel crank lengths used in the experimental trials: 120 and 220 mm (conventional crank lengths are generally in the range of 165–175 mm). Crank lengths were presented in a counterbalanced order. Seat height was based on each individual's normal seat height and adjusted up (for the 120-mm cranks) or down (for the 220-mm cranks) to compensate for the difference in their normal crank length and the experimental crank lengths. Specifically, we adjusted seat position to maintain the participant's accustomed maximum leg extension as we have done in previous investigations (14,20,22). Experimental data were collected on the second and fourth visits, which were separated by 5 or 6 d. Participants performed a 12-min warm-up at self-selected intensity before the experimental trials, and standardized verbal encouragement was given throughout the trials. Participants pedaled at the prescribed pedaling rate but with very little power for 1 or 2 s before the start of the maximal trials. The maximal isokinetic, fatiguing cycling trials were 30 s in duration, and participants were instructed to pedal as powerfully as possible on each crank revolution throughout the trial and not to adopt any pacing strategy. Pedaling rates were optimized for maximal power production (20) for each crank length. Pedaling rate was 135 rpm, and pedal speed was 1.7 $m \cdot s^{-1}$ for the 120-mm cranks (pedal speed = crank length (m) $\times$ pedal frequency (rpm) $\times$ π / 30; Fig. 1). Pedaling rate was 109 rpm, and pedal speed was 2.5 $m \cdot s^{-1}$ for the 220-mm cranks (Fig. 1).

A Monark (Vansbro, Sweden) cycle ergometer frame and flywheel were used to construct an isokinetic ergometer. The flywheel was driven by a 3750-W direct current motor (model CDP3605; Baldor Electric Company, Fort Smith, AR) via pulleys and a belt. The motor was controlled by a speed controller equipped with regenerative braking (model RG5500U; Minarik, Glendale, CA). When a cyclist applied power to the ergometer, the motor acted as a generator, and the generated current was dissipated by a resistor and heat sink built into the speed controller. The controller could, therefore, maintain a specified pedaling rate while resisting power outputs of up to 3750 W. The system was somewhat compliant such that the pedaling rate varied by approximately 3 rpm, with pedaling rate being slightly greater than

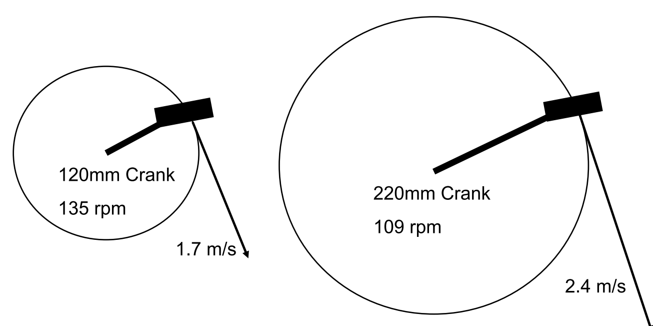

FIGURE 1—Schematic representative of the experimental conditions. The 120-mm cranks were pedaled at 135 rpm, which gave a pedal speed of 1.7 $m \cdot s^{-1}$. The 220-mm cranks were pedaled at 109 rpm, which gave a pedal speed of 2.4 $m \cdot s^{-1}$. Pedaling rate limits the time available for muscle excitation and relaxation, whereas pedal speed serves as a surrogate measure for muscle shortening velocity. These combinations produced conditions with higher pedaling rate and lower pedal speed (120-mm cranks) or lower pedaling rate and higher pedal speed (220-mm cranks). Previous research indicated that these conditions would allow production of similar maximum power values.

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the target rate early in the trial and slightly less than the target toward the end of the trial. The ergometer was equipped with a Schoberer Rad Messtechnik power meter (SRM), which has been reported to provide accurate and valid measures of power (11,19). Power and pedaling rate data were recorded at 10 Hz, and each sample represented an average over a complete revolution (11). All participants wore cycling shoes with spring-loaded cleats that locked the shoes to the pedals.

Peak power was defined as the greatest power value recorded by the SRM power meter, and minimum power was defined as the smallest power value recorded during the trial. Time-to-peak power was also identified. Fatigue index (FI) was calculated as: FI = (peak power − minimum power)/peak power. Incremental work for each sampled data point was calculated as the product of power and sampling time interval ($1/f$ = 0.1 s), and cumulative work was calculated by summing the incremental work values up to each time point including 30 s (total work). Three paired Student's t-tests were performed to test for differences in peak power output, FI, and total work. Significant differences were hypothesized for the latter two variables, and the level of significance value was adjusted by one-half (0.05/2 = 0.025) to avoid type I error. We did not expect to detect differences in peak power for the two crank lengths on the basis of previous investigations (14,18,20).

Linear and exponential regression analyses were performed to determine the relationships of power with cumulative work (as a mechanical indicator of total metabolic by-product production), cumulative pedal revolutions (representing the number of maximal contractions), and with the cumulative arc length traveled by the pedal (assumed to be proportional to the accumulated muscle shortening distance). Exponential models were included because Weyand et al. (25) and Bundle et al. (4) have

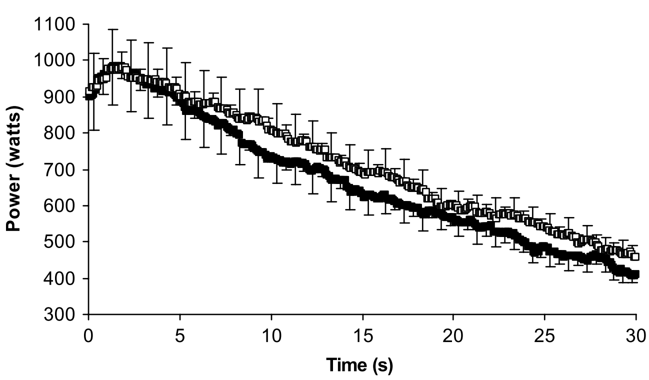

FIGURE 2—Power output versus time for all-out 30-s sprint cycling trials. Fatigue was greater when cycling with the higher pedaling rate–lower pedal speed–shorter crank length condition (■) than with lower pedaling rate–higher pedal speed–longer crank length condition (□). Error bars are only given for every fifth data point to avoid crowding the figure. Alternative error bars represent SE for all seven participants (including the one female whose power was less than half the mean of the others) and for the six male participants only.

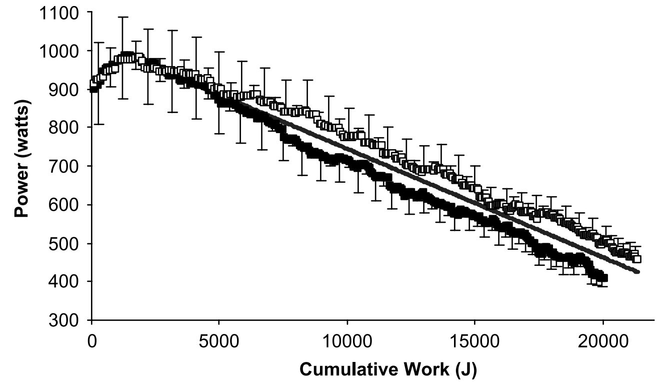

FIGURE 3—Power output versus cumulative work for all-out 30-s sprint cycling trials. Fatigue was highly related to cumulative work performed across the two conditions (r^2 = 0.941). Cumulative work serves as an indicator of the metabolic disturbance in the muscle for this model. Despite the high correlation of power and cumulative work, a treatment effect is clearly visible between the two conditions. *Closed squares* represent the high pedaling rate–low pedal speed–short crank length condition. *Open squares* represent the low pedaling rate–high pedal speed–long crank condition. *Gray line* represents the regression analysis for the combined data for the fatiguing portion of the two conditions (3–27 s).

reported that an exponential model provides an excellent fit for cycling fatigue data. For each dependent variable, only the regression model with the larger coefficient of determination was reported. Only the final 27 s of data were used in these analyses because these represented the fatiguing portion of the trial (which followed an initial period of rested and potentiated power production). These regression analyses were performed with data for each individual and with the mean data.

RESULTS

Participants reached peak power in 1.3 ± 0.7 s (mean ± SD), and power generally decreased for the remainder of the trial (Fig. 2). Mean, maximum, and minimum pedaling rates were 135 ± 1, 137 ± 1, and 134 ± 1 rpm for the 120-mm cranks and 109 ± 1, 110 ± 2, and 107 ± 1 for the 220-mm cranks, indicating that the isokinetic system controlled pedaling rate to within approximately ±1.5% of the target pedaling rates. Peak power was 999 ± 276 W for the 120-mm cranks and 1001 ± 289 W for the 220-mm cranks, and these values did not differ (P = 0.93). The large SDs in power were attributable mostly to the one participant whose peak power was less than half the mean of the other six participants but that did not influence the results of the repeated-measures design.

FI was 12% greater when cycling with the high pedaling rate–short crank condition (58.6% ± 9.9%) than with the low pedaling rate–long crank condition (52.4% ± 12.6%, P < 0.01). Total work accomplished during the trials was 7% greater when cycling with the low pedaling rate–long crank condition (21.4 ± 5.3 kJ) than the high pedaling rate–short crank condition (20.0 ± 4.7 kJ, P < 0.01). Regression analyses indicated that cumulative work (linear model) accounted for 94.1% of the variation in mean power during the final 27 s of the trials (Fig. 3) and for 88.4% ± 7.8% of the variation in power for each individual participant. Cumulative pedal revolutions (exponential model) accounted for 98.9% of the variation in mean power (Fig. 4) and for 93.3% ± 6.5% of variation in power for each individual participant. Cumulative arc length (linear model) accounted for 68.6% of the variation in mean power (Fig. 5) and for 64.4% ± 8.4% of the variation in power for each individual participant.

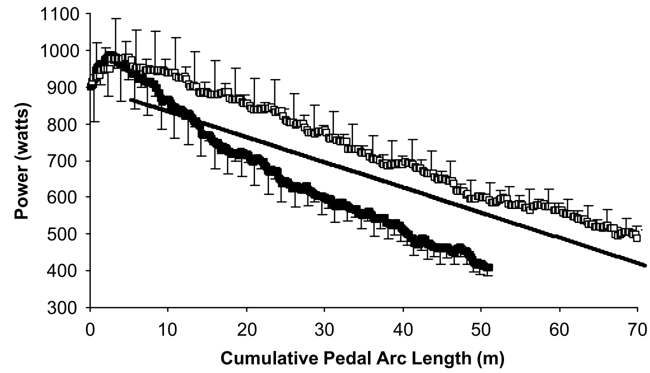

FIGURE 5—Power output versus cumulative arc length for all-out 30-s sprint cycling trials. Fatigue was not as highly related to cumulative pedal arc length across the two conditions (r^2 = 0.686). Cumulative arc length was used as a surrogate measure to approximate total length shortened by the muscles. The data suggest that shortening velocity and/or shortening length was not a major contributor to fatigue. *Closed squares* represent the high pedaling rate–low pedal speed–short crank length condition. *Open squares* represent the low pedaling rate–high pedal speed–long crank condition. *Gray line* represents the regression analysis for the combined data for the fatiguing portion of the two conditions (3–27 s).

DISCUSSION

In support of our hypothesis, fatigue was greater when cycling at 135 rpm and 1.7 $m \cdot s^{-1}$ with a 120-mm crank length than when cycling at 109 rpm and 2.5 $m \cdot s^{-1}$ with a 220-mm crank length. This finding of increased fatigue with increased pedaling rate supports previous research (3,21) and addressed two additional questions. First, peak power produced during the initial portion of our experimental trials did not differ for the two treatments, indicating that subsequent differences in fatigue were not attributable to differences in work accomplished in the initial portion of the trial. Differences in initial power and work would likely influence the accumulation of metabolic by-products such as P_i and ADP, which are reported to inhibit force production (9,23). Thus, our data support previous findings and strengthen them by eliminating the possibility that they were biased by differences in initial power or work and associated disturbances in the metabolic milieu within the muscle. Second, because previous investigators (3,21) used a single crank length, pedaling rate and pedal speed were linearly coupled, and the relative importance of each term could not be determined. Our use of two crank lengths allowed us to differentiate the effects of pedaling rate from those of pedal speed and indicated that the key parameter for increased fatigue was indeed pedaling rate.

Pedaling rate, or, in the broader context of repetitive cyclic muscle contraction, cycle frequency, prescribes the time available for muscle excitation and relaxation. Caiozzo and Baldwin (6) have reported that increased cycle frequency reduces average muscular excitation during a cycle. When pedaling at 135 rpm (2.25 Hz), a cycle would occur in 0.444 s, and thus, approximately 0.222 s was available for each phase of the cycle (flexion and extension). When pedaling at 109 rpm (1.82 Hz), each cycle would occur in 0.55 s, and approximately 0.275s was available for each phase. This 24% increase in time for the lower pedaling rate condition likely allowed for increased average muscle excitation within each phase, which may have been partially responsible for the reduced fatigue we observed.

Pedal speed, which serves as an indicator of average muscle shortening velocity (14,27) increases with increasing pedaling rate for any specific crank length. Increased muscle shortening velocity may contribute to increased fatigue because maximum shortening velocity has been reported to be reduced with fatigue (7). Such a change in the force–velocity relationship would reduce power to a greater extent at high muscle shortening velocities. Our data indicated that fatigue was reduced in the higher pedal speed condition, suggesting that the role of muscle shortening velocity in fatigue was not substantial in this experimental design. On the basis of these results, we conclude that the dominant parameter responsible for greater rates of fatigue previously reported to occur with

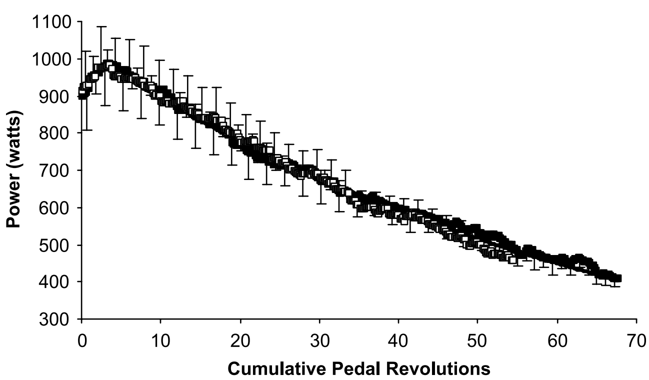

FIGURE 4—Power output versus cumulative pedal revolutions for all-out 30-s sprint cycling trials. Fatigue was highly related to cumulative pedal revolutions across the two conditions (r^2 = 0.989). Cumulative crank revolutions eliminated treatment effect differences, and the relationship indicated that power decreased similarly with each crank revolution. These data suggest that each maximal contraction exacted a specific amount of fatigue that was separate from the fatigue associated with mechanical work. *Closed squares* represent the high pedaling rate–low pedal speed–short crank length condition. *Open squares* represent the low pedaling rate–high pedal speed–long crank condition. *Gray line* represents the regression analysis for the combined data for the fatiguing portion of the two conditions (3–27 s).

increased pedaling rates was pedaling rate *per se*, which limits time available for muscle excitation and relaxation.

In addition to the pairwise treatment comparisons, our regression analyses provided a means to further explore our fatigue data and identify variables that might account for differences in data for the two conditions. As hypothesized, cumulative work accounted for a large portion of the variation in power (94.1% for the mean data) across our two conditions. Because this was a short-term maximal effort, work was likely supported mainly by anaerobic metabolism, and thus, total work can serve as a general indicator of disturbance of homeostasis in the metabolic milieu (12). During such an effort, the stores of, and energy derived from, ATP and creatine phosphate (P_{CR}) are limited and quickly depleted; intramuscular pH is reduced, affecting the activity of glycolytic enzymes; and accumulation of intracellular P_i impairs cross-bridge cycling and calcium handling (24). The tight coupling of fatigue and cumulative work exhibited by our data may therefore represent incremental depletion of P_{CR}, reduction of cellular pH, and accumulation of P_i. Indeed, this tight coupling suggests that our treatments, which involved large differences in pedaling rate, pedal speed, and crank length, elicited relatively small changes in fatigue as confirmed by the 7% difference in total work.

Although power was highly related to cumulative work, differences between our two treatments were clearly evident (Fig. 3). These differences were mostly attributable to the number of cumulative pedal revolutions (Fig. 4). Specifically, cumulative pedal revolutions accounted for 98.9% of the variation in mean power across the two conditions. Power data from the two conditions essentially converged onto a single relationship with cumulative pedal revolutions. This convergence suggests that each maximal contraction cycle, regardless of pedaling rate, exacted an increment of fatigue such that the next pedal cycle was performed with less power. From this point of view, the increased fatigue associated with increased pedaling rate occurred simply because more revolutions were completed within the 30-s trial. This finding is beyond our stated hypothesis and requires us to consider alternative mechanisms that might act on a per-contraction basis. A potential peripheral mechanism could be fatigue of the calcium pumping action (1,5,26), which would reduce relaxation (as we hypothesized) and act progressively with each contraction. Alternatively, fatigue data reported by Weyand et al. (25) and Bundle et al. (4) may provide support for a central explanation because, in their model, EMG amplitude increased throughout fatiguing exercise trials such that maximum EMG amplitude and failure to maintain the target power occurred simultaneously. Within the scope of our present data, exact determination of the mechanism responsible remains speculative, but we believe our findings will provide a framework for future research.

An apparent practical application of our findings is that it could guide competitive cyclists who participate in fatiguing maximal events (sprint and 500- or 1000-m time trial) with their crank length selection. Competitive cyclists usually select cranks within the commercially available range of 165 to 175 mm, which is substantially smaller than the range used in the present study. On the basis of previous work by Martin and Spirduso (20), the optimal pedaling rate for 165- and 175-mm crank lengths would range from approximately 121 rpm for the 175-mm cranks to 124 rpm for the 165-mm cranks (20). On the basis of our regression analyses of fatigue and cumulative cycles (Fig. 4), this difference of 3 rpm in optimal pedaling rate would elicit a change of only 0.7% in FI for a 30-s maximal trial. Because power is roughly related to speed cubed (15,17,19), such a change in power would decrease speed by only approximately 0.2% by the end of a 30-s trial. If the change in fatigue occurred progressively during the 30-s trial, the change in average speed would be approximately 0.1% equating to a change of approximately 0.03 s for a fixed distance time trial of approximately 30 s (such as a 500-m time trial). Further, because optimal pedaling rate occurs at the apex of the power–pedaling rate relationship, cyclists could alter pedaling rate by 3 rpm to compensate for differences in rates of fatigue without substantially altering power (e.g., 0.06% based on a quadratic power–pedaling rate with an apex at 121 rpm). Thus, although the findings of this study imply that longer cranks, which allow maximum power production at a lower pedaling rate, could provide a performance advantage, the practical implications are essentially negligible, and cyclists may select crank lengths on the basis of criteria other than fatigue resistance.

An alternative explanation of our results and a potential limitation to our study design is that differences in crank length may have resulted in alterations in relative joint power production. This may influence fatigue because Martin and Brown (13) recently reported that the power produced at the hip was more fatigue-resistant than the power produced at the knee and ankle. If cycling power with the 120-mm crank length was produced with relatively greater reliance on knee and ankle power (more fatigable), the differences we observed might be attributable, at least partly, to joint-specific fatigue. Biomechanical joint power data for maximal cycling with crank lengths of 120 and 220 mm have not been reported, and we cannot rule this out as an explanation for our findings. Given that the peak power produced in our two treatments was essentially equal (999 vs 1001 W), it seems unlikely that such similar power values would have been produced with different joint power profiles. Nonetheless, this is a current area of interest for our laboratory, and work is underway on the effects of crank length and joint power production.

In summary, our data indicate that the increased fatigue associated with increased pedaling rate previously reported is indeed related to pedaling rate rather than pedal speed. This finding supports the notion that the time available for muscle excitation and relaxation kinetics is a major contributor to fatigue and can be interpreted to suggest that changes in calcium handling and calcium pumping actions are the mechanisms most likely responsible for increased fatigue. Our regression analyses indicated that our treatment effect was closely associated with the number of crank revolutions, or individual maximal contractions, rather than pedaling rate *per se*. This observation is completely novel, and we interpret the data to indicate that reduced calcium pumping action or reduced central drive is responsible for differences in fatigue with different pedaling rates. We believe that the present data will serve as bases for future research designed to elucidate fatigue mechanisms that might act on a per-contraction basis during maximal exercise.

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REFERENCES

1. Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev*. 2008;88(1):287–332.
2. Bar-Or O, Dotan R, Inbar O. A 30-second all-out ergometric test—its reliability and validity for anaerobic capacity. *Isr J Med Sci*. 1977;13:126.
3. Beelen A, Sargeant AJ. Effect of fatigue on maximal power output at different contraction velocities in humans. *J Appl Physiol*. 1991;71(6):2332–7.
4. Bundle MW, Ernst CL, Bellizzi MJ, Wright S, Weyand PG. A metabolic basis for impaired muscle force production and neuromuscular compensation during sprint cycling. *Am J Physiol Regul Integr Comp Physiol*. 2006;291(5):R1457–64.
5. Byrd SK, McCutcheon LJ, Hodgson DR, Gollnick PD. Altered sarcoplasmic reticulum function after high-intensity exercise. *J Appl Physiol*. 1989;67(5):2072–7.
6. Caiozzo VJ, Baldwin KM. Determinants of work produced by skeletal muscle: potential limitations of activation and relaxation. *Am J Physiol*. 1997;273(3 Pt 1):C1049–56.
7. De Ruiter CJ, Jones DA, Sargeant AJ, De Haan A. The measurement of force/velocity relationships of fresh and fatigued human adductor pollicis muscle. *Eur J Appl Physiol Occup Physiol*. 1999;80(4):386–93.
8. Favero TG. Sarcoplasmic reticulum Ca(2+) release and muscle fatigue. *J Appl Physiol*. 1999;87(2):471–83.
9. Fitts RH. The cross-bridge cycle and skeletal muscle fatigue. *J Appl Physiol*. 2008;104(2):551–8.
10. Gardner A, Martin D, Jenkins D, et al. Velocity specific fatigue: quantifying fatigue during variable velocity cycling. *Med Sci Sports Exerc*. 2009;41(4):904–11.
11. Gardner AS, Stephens S, Martin DT, Lawton E, Lee H, Jenkins D. Accuracy of SRM and power tap power monitoring systems for bicycling. *Med Sci Sports Exerc*. 2004;36(7):1252–8.
12. Glaister M. Multiple sprint work: physiological responses, mechanisms of fatigue and the influence of aerobic fitness. *Sports Med*. 2005;35(9):757–77.
13. Martin JC, Brown NA. Joint-specific power production and fatigue during maximal cycling. *J Biomech*. 2009;42(4):474–9.
14. Martin JC, Brown NA, Anderson FC, Spirduso WW. A governing relationship for repetitive muscular contraction. *J Biomech*. 2000;33(8):969–74.
15. Martin JC, Davidson CJ, Pardyjak ER. Understanding sprint–cycling performance: the integration of muscle power, resistance, and modeling. *Int J Sports Physiol Perform*. 2007;2(1):5–21.
16. Martin JC, Diedrich D, Coyle EF. Time course of learning to produce maximum cycling power. *Int J Sports Med*. 2000;21(7):485–7.
17. Martin JC, Gardner AS, Barras M, Martin DT. Modeling sprint cycling using field-derived parameters and forward integration. *Med Sci Sports Exerc*. 2006;38(3):592–7.
18. Martin JC, Malina RM, Spirduso WW. Effects of crank length on maximal cycling power and optimal pedaling rate of boys aged 8–11 years. *Eur J Appl Physiol*. 2002;86(3):215–7.
19. Martin JC, Milliken DL, Cobb JE, McFadden KL, Coggan AR. Validation of a mathematical model for road cycling power. *J Appl Biomech*. 1998;14(3):276–91.
20. Martin JC, Spirduso WW. Determinants of maximal cycling power: crank length, pedalling rate, and pedal speed. *Eur J Appl Physiol*. 2001;84(5):413–8.
21. McCartney N, Heigenhauser GJ, Jones NL. Power output and fatigue of human muscle in maximal cycling exercise. *J Appl Physiol*. 1983;55(1):218–24.
22. McDaniel J, Durstine JL, Hand GA, Martin JC. Determinants of metabolic cost during submaximal cycling. *J Appl Physiol*. 2002;93(3):823–8.
23. McLester JR Jr. Muscle contraction and fatigue. The role of adenosine 5′-diphosphate and inorganic phosphate. *Sports Med*. 1997;23(5):287–305.
24. Westerblad H, Allen DG, Lannergren J. Muscle fatigue: lactic acid or inorganic phosphate the major cause? *News Physiol Sci*. 2002;17:17–21.
25. Weyand PG, Lin JE, Bundle MW. Sprint performance–duration relationships are set by the fractional duration of external force application. *Am J Physiol Regul Integr Comp Physiol*. 2006;290(3):R758–65.
26. Williams JH, Klug GA. Calcium exchange hypothesis of skeletal muscle fatigue: a brief review. *Muscle Nerve*. 1995;18(4):421–34.
27. Yoshihuku Y, Herzog W. Optimal design parameters of the bicycle–rider system for maximal muscle power output. *J Biomech*. 1990;23(10):1069–79.