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Conference Abstract

Understanding Optimal Cadence Dynamics: A Systematic Analysis of the Power-Velocity Relationship in Track Cyclists with Increasing Exercise Intensity

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Abstract:

Background: The relationship between cadence and cycling performance is a critical yet complex aspect of sports science. This study investigates whether training zone programs should be adjusted to different cadences, addressing a gap in current understanding. Previous research has shown that cadence significantly influences metabolic responses across various exercise intensities, affecting blood lactate concentration, cardiac output, and respiratory measures (Michaelis & Müller 1942; Hess & Seusing, 1963; Eckermann & Millahn, 1967; Israel et al., 1967; Pugh, 1974; Gaesser & Brooks, 1975; McKay & Banister, 1976; Schürch et al., 1976; Seabrug et al., 1977; Löllgen et al., 1980; Hagberg et al., 1981; Böning et al., 1984; Chavarren & Calbet, 1999; Zoldaz et al., 2000; Foss & Hallén, 2004; Beneke et al., 2015; Beneke et al., 2018). Established parabolic functions describe the relationship between metabolic or cardiopulmonary states and cadence at specific work rates (Böning et al.; 1984; Zoldaz et al., 2000), revealing an inverted U-shaped relationship between power and velocity, even at submaximal intensities.

Based on the observation that cadence corresponding to the minimum metabolic cost increases with rising work rates, the optimal cadence (PR_{opt}) for maximizing power output at equal metabolic costs appears to increase with exercise intensity (Coast & Welch, 1985; Zoladz et al., 2000). This increase is likely due to the recruitment of faster-twitch muscle fibers (Macintosh et al., 2000; Sanderson et al., 2006). However, the systematic pattern of this relationship across submaximal to maximal intensities remains unclear.

By analyzing force-velocity and power-velocity relationships across different metabolic states, this study aims to elucidate the change in optimal cadence with increasing work rate and examine the optimal pedaling rate at characteristic metabolic thresholds. We hypothesize a systematic increase in optimal cadence with rising work intensity, potentially indicating the progressive recruitment of faster-twitch muscle fibers.

Methods: Fourteen professional track cyclists (9 sprinters, 5 endurance athletes) performed submaximal incremental tests, high-intensity cycling trials, and maximal sprints at varied cadences (60, 90, 120 rpm) on an SRM bicycle ergometer. The protocol is illustrated in Figure 1.

Mechanical power output (P), pedaling rate (PR), heart rate (HR), respiratory gases, and blood lactate concentration (BLC) were measured. Linear and non-linear regression analyses were used to assess the relationship between heart rate, oxygen uptake (VO_2), blood lactate concentration and power output at each pedaling rate (see Figure 2).

Work rates linked to various cardiopulmonary and metabolic states, including lactate threshold (LT1), maximal fat combustion (FAT_{max}), maximal lactate steady-state (MLSS) and maximal oxygen uptake (VO_{2max}), were determined using cadence-specific inverse functions (see Figure 3.)

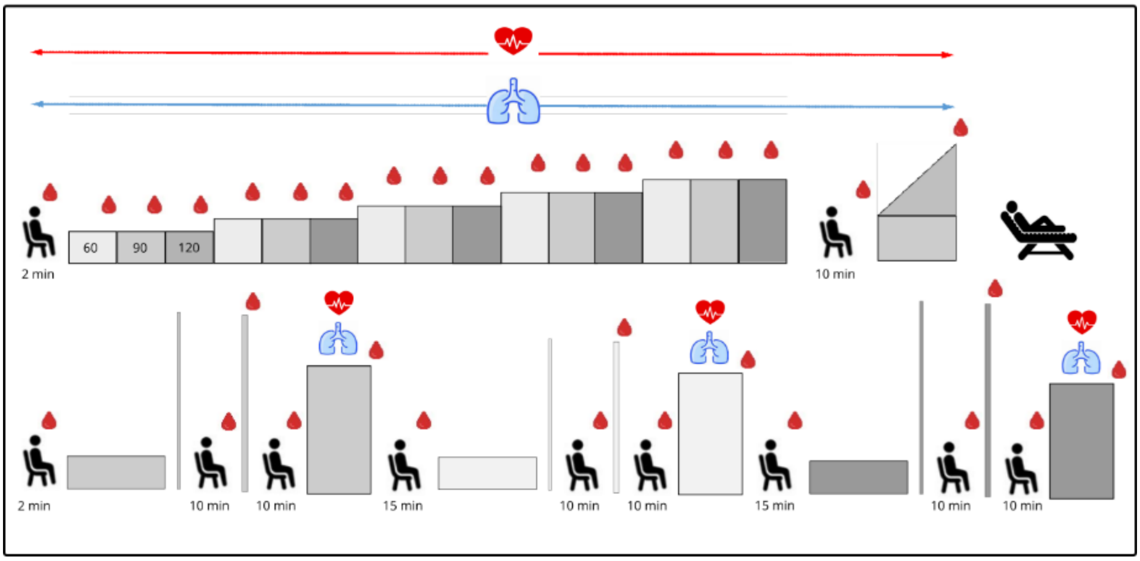

Figure 1. Schematic schedule of the test battery, which included a submaximal incremental test with cadence changes of 60, 90, and 120 rpm every 3 minutes and intensity increments of 40 W every 9 minutes, starting at 100 W and continuing until a blood lactate concentration of 4 mmol l^{-1} was reached. Additionally, three maximal 6-second sprint tests and three 4-minute high-intensity constant load tests were performed at the same cadences. Measurements included mechanical power output, pedaling rate, heart rate, respiratory gases, and blood lactate concentration.

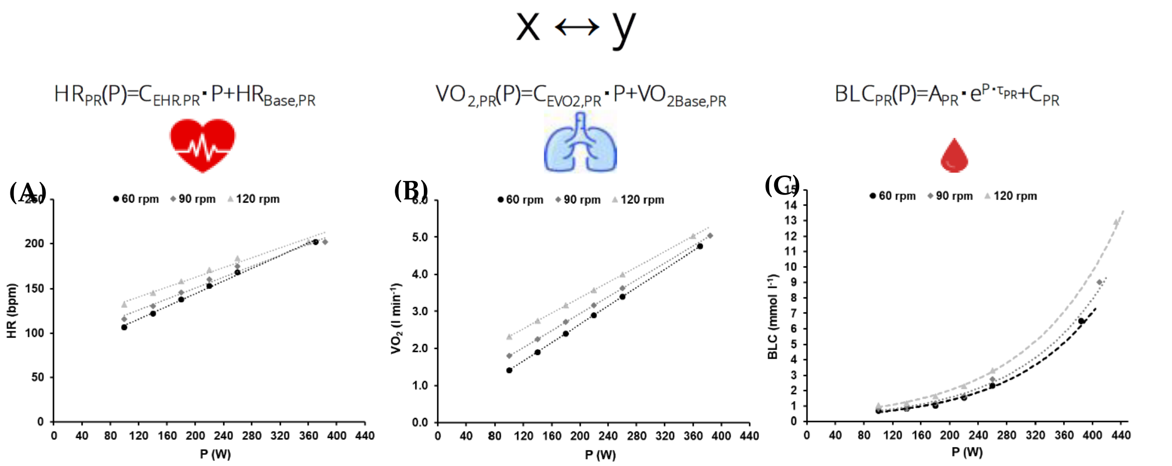

Figure 2. Mean heart rate (A), oxygen uptake (b) and blood lactate concentration (C) at work rates ranging from 100-260 W and at ≥ 90% of maximum aerobic power for the three different pedaling rates with the corresponding linear and exponential relationships.

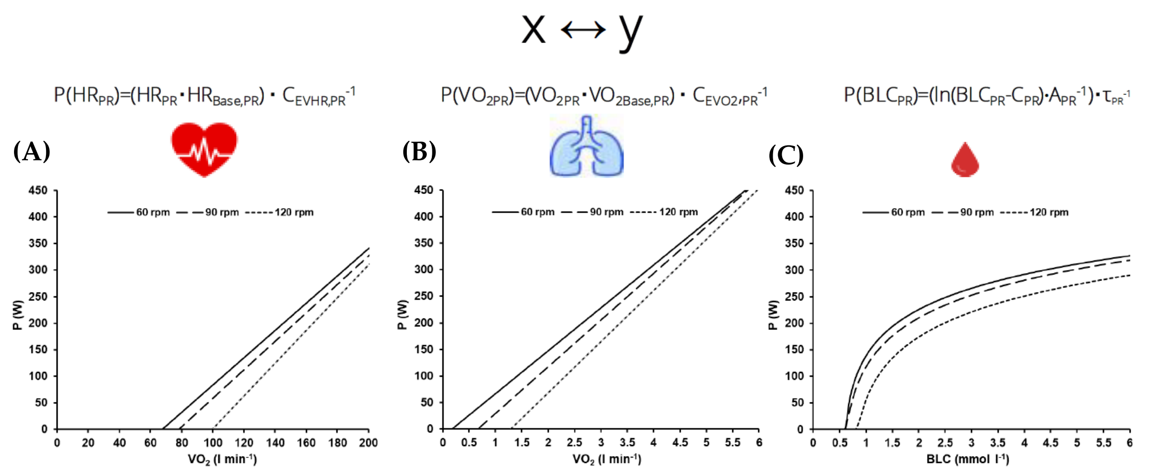

Figure 3. Inverse relationship between power output and heart rate (A), oxygen uptake (B) and blood lactate concentration (C) for the three different pedaling rates.

These data were used to calculate state-specific force-velocity (F/v) and power-velocity (P/v) profiles, from which state-specific optimal cadences were derived. Figure 4 provides a representative example illustrating the calculation method. Additionally, fatigue-free profiles were generated from sprint data to illustrate the entire force-velocity (F/v) and power-velocity (P/v) continuum, following the method described by Dunst et al. (2023).

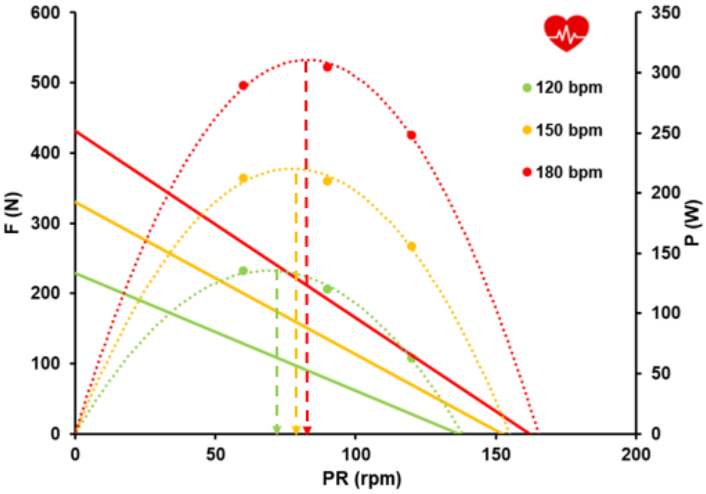

Figure 4. Exemplary power-velocity and corresponding force-velocity profiles at heart rates of 120 bpm, 150 bpm, and 180 bpm. Vertical dashed lines indicate the cardiac stress-specific maximal power output and its corresponding optimal cadence.

Results: HR, VO_2 demonstrated linear relationships, while BLC exhibited an exponential relationship with work rate, influenced by cadence ($p < 0.05$, η2   0.655). Optimal cadence increased sigmoidally across all parameters as demonstrated in Figure 5.

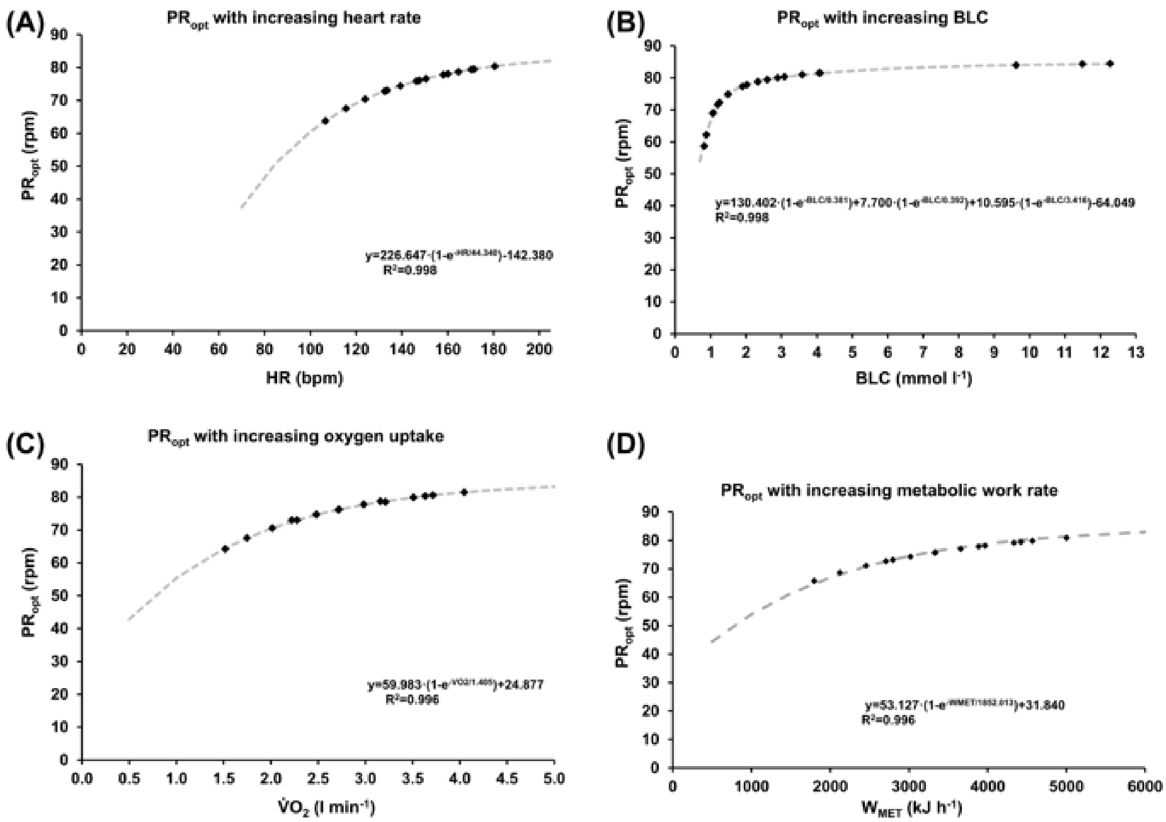

Figure 5. Optimal pedaling rate progression across physiological indicators: heart rate (A), blood lactate concentration (B), oxygen uptake (C), total metabolic energy (D). Sigmoidal increase in PR_{opt} from very low intensity to maximum aerobic power (Dunst et al., 2024).

The optimal cadence at various metabolic thresholds was found to be 66.18 ± 3.00 rpm at LT1, 76.01 ± 3.36 rpm at FAT_{max}, 82.24 ± 2.59 rpm at MLSS, and 84.49 ± 2.66 rpm at VO_{2max} ($p < 0.01$, $\eta = 0.936$). Additionally, a fatigue-free optimal cadence of 135 ± 11 rpm was identified. There were no significant differences in optimal cadences between sprinters and endurance athletes, except for the fatigue-free optimum ($p < 0.001$, $d = 2.215$). These mean profiles are illustrated in Figure 6.

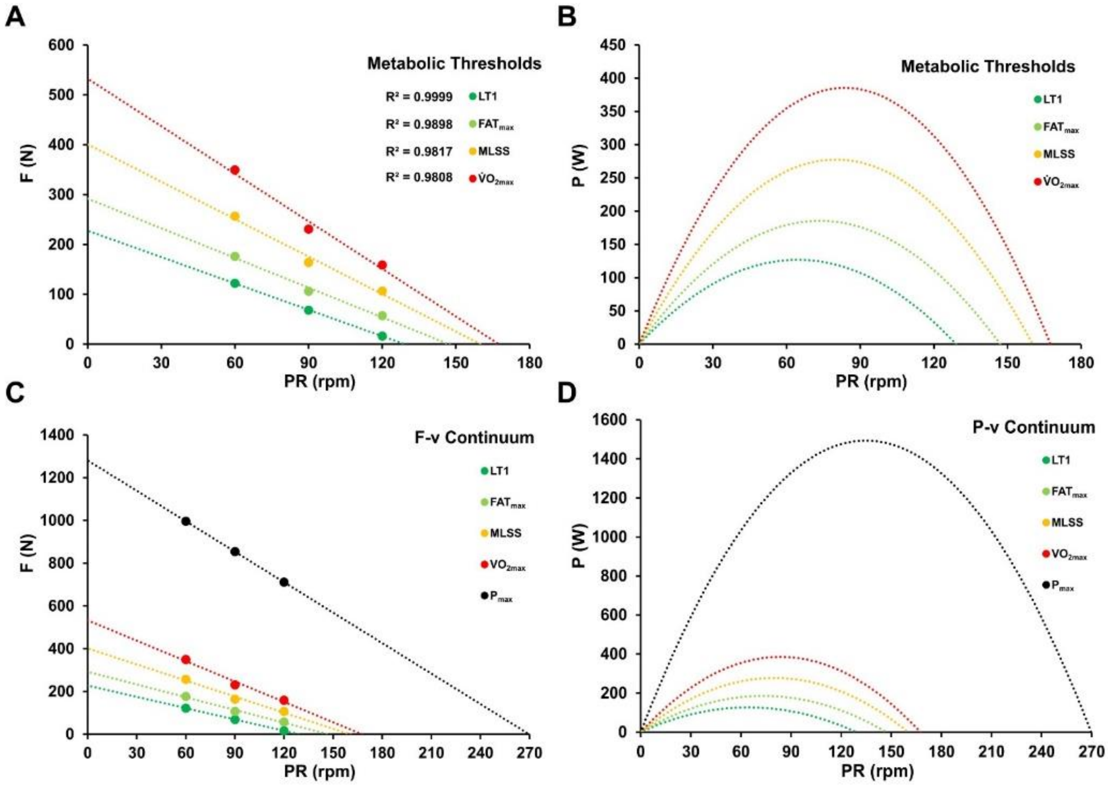

Figure 6. Force-velocity (A, C) and power-velocity profiles (B, D) at various metabolic thresholds (LT1, FAT_{max}, MLSS) and at maximal power output (PVO_{2max}) (Dunst et al., 2024).

Conclusion: In summary, our study reveals a consistent, sigmoidal increase in optimal cycling cadence with intensity, ranging from 45 rpm at very low intensities to 84 rpm at maximal aerobic effort, regardless of the physiological response considered. At characteristic metabolic states, PR_{opt} significantly increased from 65 rpm at LT1 to 84 rpm at VO_{2max}, with minimal inter-individual variations. State-specific changes in optimal pedaling rate suggest increased recruitment of faster muscle fiber types with rising intensity and velocity, highlighting the need to expand Henneman's hierarchical size principle by incorporating the dimension of movement velocity. Our findings challenge the accuracy of the current cadence-independent formulation of the mean-max-power curve, of two-dimensional metabolic profiles and training zones by highlighting the crucial role of movement velocity.

Consequently, we recommend presenting intensity zones as a function of movement velocity rather than in absolute terms, and adjusting training programs accordingly. Figure 8 illustrates a possible adjustment of work rate prescriptions at metabolic thresholds for target cadences of 60 rpm and 120 rpm, compared to the power output calculated for a cadence of 90 rpm based on performance diagnostics.

Our findings can help to understand the physiological concept of optimal cadence and may help cyclists optimize performance by adjusting cadence according to work rates and metabolic states, potentially enhancing overall cycling performance.

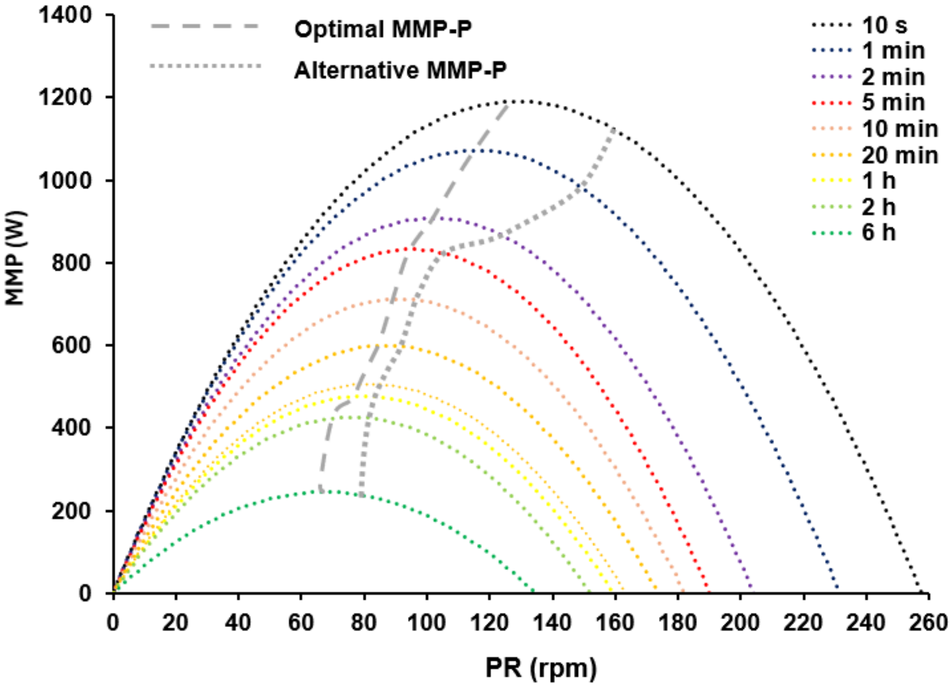

Figure 7. Illustration of the implications of our results for the mean-max-power curve (MMP-P); cadence influences maximal mean power output across different time durations, demonstrating the importance of considering movement velocity in performance analysis and in training and pacing prescriptions.

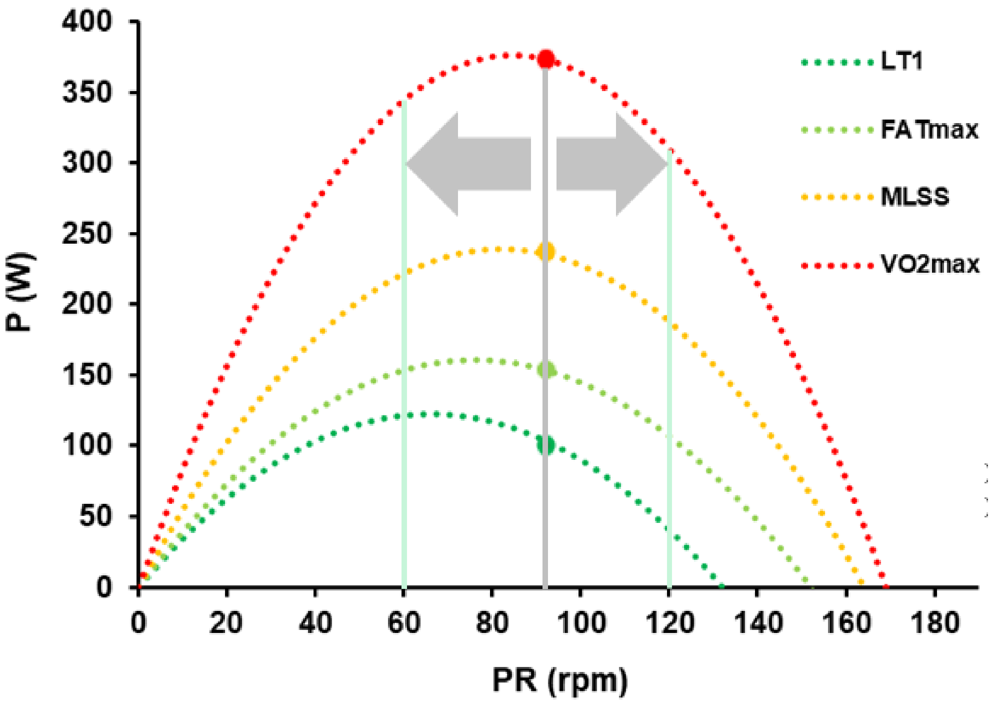

Figure 8. Figure 8. Adjustment of work rate prescriptions at metabolic thresholds for target cadences of 60 rpm and 120 rpm. The figure compares the power output calculated for a cadence of 90 rpm based on performance

diagnostics. The adjustments highlight the relationship between cadence and power output, emphasizing the need to tailor training programs according to movement velocity rather than absolute intensity zones.

Keywords: Optimal Pedaling Rate, Muscle Fiber Recruitment, Power-Velocity Profiles, Force-Velocity Profiles, Exercise Physiology, Mathematical Modelling, Size Principle

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Abbreviations

A_{PR}	Cadence-specific amplitude of blood lactate concentration
BLC	Blood lactate concentration
bpm	Heartbeats per minute, nit of heartrate
C_{PR}	Cadence-specific baseline level of blodc lactate concentration
C_EHR_{PR}	Cadence-specific cycling efficiency for heartrate in beats per minute per watt
C_EVO_{2PR}	Cadence-specific cycling efficiency for oxygen uptake in milliliters oxygen uptake per watt
F	Force, mean pedal force
FAT_{max}	Work rate associated with the peak fat oxidation
F/v	Force-velocity relationship
HR	Heart rate
$HR_{Base,PR}$	Cadence-specific baseline level of heart rate
LT1	First lactate threshold, highest work rate without significant blood lactate accumulation
MLSS	Maximal lactate steady-state
MMP	Mean maximal power
P	Mechanical power output
P/v	Power-velocity relationship
PR_{opt}	Cadence at maximal power output, optimal pedaling rate
PVO_{2max}	Power output at maximum oxygen uptake
rpm	Crank revolutions per minute
τ	Tau, constant of kinetic
VO_2	Oxygen uptake
$VO_{2Base,PR}$	Cadence-specific baseline level of oxygen uptake
VO_{2max}	Test specific maximal oxygen uptake
W_{MET}	Metabolic cost