

Research Article

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Associations of strength indices and cycling economy in young adults

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Abstract

Objectives: Cycling economy is associated with muscle strength in athletes. However, the relationship between strength capacity (i.e. maximal and explosive strength) and cycling economy in previously untrained but healthy individuals remains unclear. Therefore, this study aimed to assess the associations between cycling economy and strength performance in a population of recreationally active but untrained healthy individuals.

Methods: A total of 155 recreationally active individuals (95 males and 60 females) were included. Strength capacity was assessed through an incremental one-repetition maximum test, from which the one-repetition maximum, mean propulsive velocity, and mean propulsive power were derived as strength indices. Cycling economy was assessed using a step protocol on a cycle ergometer and gross oxygen cost and caloric unit cost were determined at submaximal intensities.

Results: Marginal R^2 ranged between 0.013 and 0.062 for the gross oxygen cost and between 0.022 and 0.103 for the gross caloric unit cost, respectively. Greater cycling economy is related to higher strength levels. However, the relationship is relatively weak, explaining only 1.3–6.2 % of the variance in gross oxygen cost and 2.2–10.3 % of the variance in gross caloric unit cost.

Conclusions: Greater cycling economy in recreationally active males and females is related to higher strength levels

(i.e. one-repetition maximum, mean propulsive velocity, mean propulsive power).

Keywords: physical activity; cycling economy; oxygen consumption; maximal strength; gross caloric unit cost

Introduction

Traditionally, the maximum oxygen consumption ($\dot{V}O_{2max}$) is considered a performance determinant in recreational and elite sports [1] but has also been shown to be a risk factor of cardiovascular diseases in untrained populations [2]. Similarly, also movement economy (i.e. oxygen consumption at given submaximal loads) may be important for endurance performance [3, 4], but may also be linked to energy conservation in the general population. In a previous study it was shown that individuals with higher cardiovascular demands exhibit lesser daily stepping time [5]. Thus, by promoting efficient movement, the overall energy expenditure required for daily activities is minimized, allowing individuals to undertake tasks with greater ease and diminished fatigue [5, 6].

Understanding the mechanism behind fluctuations in movement economy is eminent but conclusive evidence is lacking. In athletic populations, it was shown that a greater percentage of type I fibers is related to better movement economy, as this fiber type is known to be more efficient compared to type II fibers [7]. Furthermore, in athletic populations regular heavy strength training was shown to improve movement economy [4], primarily due to enhanced neuromuscular function [8]. In a similar manner, associations between strength capacity and movement economy were also shown in previously untrained healthy [9] as well as diseased populations [10], underlining the importance of maintaining strength to perform also habitual activities with lower energetic demands [9].

While the associations between muscle strength and walking or running have been demonstrated in non-athletic populations [9, 10], evidence is lacking for cycling. Although the link between muscle strength and cycling

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economy is known in athletes [4, 8], its manifestation in healthy and active individuals remains unclear. Therefore, this study aimed to assess the associations between cycling economy and strength performance in a population of recreationally active but otherwise untrained healthy individuals. Expanding on previous research, we hypothesized that a higher maximal as well as explosive strength is a key indicator of enhanced cycling economy. The summary of this article is presented in Figure 1.

Materials and methods

Study design

All participants completed three laboratory sessions. The first session involved familiarization with the materials and methods used in this study. The second session included an incremental ergometer test on a stationary bicycle, and the third session involved an incremental one-repetition maximum (1RM) test in the squat, with each session being



Figure 1: Graphical representation of this article. Figure created with BioRender.

separated by at least 48 h but not exceeding 5 days. However, as previous research has indicated that ovarian hormones may impact both endurance and strength performance in women, the experimental sessions (i.e. incremental ergometer test and incremental maximal strength test) were conducted at fixed points within the menstrual cycle [11]. Accordingly, the incremental ergometer test was performed within the luteal phase of the menstrual cycle, while the incremental maximal strength test was performed between days 2 and 5 of the subsequent menstrual cycle.

Participants

Participants were eligible if they met the following criteria: (1) non-smokers; (2) free from chronic or acute injuries; (3) aged between 18 and 40; and (4) physically active, but not specifically endurance and/or strength trained (more than two sessions per week). The study included both male and female participants. For female participants, only those who had a consistent menstrual cycle with regular menstrual bleedings for at least three consecutive months before participating in the study were eligible. Information regarding the menstrual cycle and monthly bleeding was obtained during a familiarization interview. Prior to inclusion, all participants received instructions regarding potential risks and provided written informed consent. This study received approval from the local institutional board and adhered to the principles of the Declaration of Helsinki. Initially, 96 males and 61 females were enrolled into the study. Two datasets (i.e. 1 male, 1 female) were excluded due to compromised $\dot{V}O_2$ data quality.

Incremental ergometer test

Participants underwent a graded exercise test on an electronically braked cycle ergometer (ergoline GmbH, Bitz, Germany) until volitional exhaustion. Before the test began, body mass was measured using a Sanitas system (Hans Dinslage GmbH, Uttenweiler, Germany). The test commenced with a 5-min warm-up at 80 W for males and 50 W for females. Subsequently, the resistance was incremented every 3 min by 30 W. Gas exchange was analysed using a Metalyzer 3B, which was calibrated according to manufacturer's recommendations before each test (Cortex, Leipzig, Germany). The $\dot{V}O_{2peak}$ was determined as the highest 30-s average. Subsequently, $\dot{V}O_{2peak}$ was utilized to quantify the level of physical fitness and to analyse its effects on cycling economy.

The gross oxygen cost of cycling ($\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) was calculated during the final minute of each increment. Additionally, the gross caloric unit cost of cycling ($\text{kcal}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) was obtained according to previous recommendations [12]. Capillary blood samples (20 μL) were collected from the earlobe, inserted into reaction capsules containing a haemolyzing agent, and then analysed using a Biosen analyser (Biosen S-Line, EKF Diagnostics, Barleben, Germany). Blood lactate concentrations were assessed at rest and in the final 20 s of each increment, in order to quantify the exercise intensity with the incremental ergometer test.

Incremental maximal strength test

We evaluated strength capacity using load-velocity and load-power profiles during squats, from which we derived the one-repetition maximum (1RM), as well as mean propulsive velocity (MPV) and mean propulsive power (MPP) as strength indicators. The MPV as well as the eccentric displacement was recorded during each repetition using a linear velocity transducer (T-Force System, Ergotech, Murcia, Spain). The propulsive phase was defined as the part of the concentric movement where the measured acceleration exceeded gravitational acceleration. Velocity was sampled at a frequency of 1,000 Hz and processed using custom software (T-Force Dynamic Measurement System, version 2.3).

The test began with a 5-min individualized warm-up on a stationary cycle ergometer, followed by 10 squats using only the participant's body weight and then 3–6 repetitions with the Smith machine barbell (22 kg). Depth and foot positioning were recorded to ensure consistency across all sets. Prior to each set, participants were instructed to maintain a controlled eccentric phase until the reversal point, hold the position for 1.5 s, and then perform the concentric phase with maximal velocity in a non-ballistic manner. Starting with an initial load of 22 kg, the load was progressively increased until participants could no longer lift the weight with correct technique. Load increments and the number of repetitions were adjusted based on the velocity achieved during each set. Three, two, and one repetitions were performed for high ($\text{MPV} > 1.0 \text{ m}\cdot\text{s}^{-1}$), moderate ($0.75 \text{ m}\cdot\text{s}^{-1} \leq \text{MPV} \leq 1.0 \text{ m}\cdot\text{s}^{-1}$), and low velocities ($\leq 0.75 \text{ m}\cdot\text{s}^{-1}$), respectively [13]. Rest between sets was set at 2 min.

Following the test, individual load-velocity and load-power characteristics were calculated. A linear regression was used to assess MPV at 30 %, 50 %, 70 %, and 90 % of the 1RM, while a third-degree polynomial was fitted to the MPP data.

Statistical analyses

To determine the associations of load-velocity and load-power characteristics (i.e. MPV, MPP & 1RM) with the gross oxygen cost and the gross caloric unit cost of cycling across different sub-maximal workloads, we used a generalized estimating equation model (GEE), since GEE allows for the consideration of correlations between repeated measurements or observations (e.g., 6 cluster). GEE models were calculated using submaximal intensities identified by blood lactate concentrations below $4 \text{ mmol}\cdot\text{L}^{-1}$, excluding heavy and severe exercise intensities due to the impact of the $\dot{V}\text{O}_{2\text{peak}}$ slow component [14]. Predictors included the following strength indices, 1RM as well as MPVs and MPPs at 30 %, 50 %, 70 %, & 90 % of 1RM. We analysed potential confounding factors such as sex and $\dot{V}\text{O}_{2\text{peak}}$ that could influence movement economy, and found that only $\dot{V}\text{O}_{2\text{peak}}$ demonstrated a significant effect on both gross oxygen cost and gross caloric cost. Moreover, research has highlighted $\dot{V}\text{O}_{2\text{peak}}$ as a factor impacting exercise economy [15], while evidence from a previous study indicates that strength levels do not affect movement economy differently between men and women [9]. Consequently, the final GEE modelling incorporated $\dot{V}\text{O}_{2\text{peak}}$ as a confounding variable in the model, along with strength indices as predictors. To mitigate multicollinearity among predictors, GEEs were computed for each strength determinant individually. Main effects were examined for each predictor across all workloads. The goodness of fit for the GEE was assessed by examining quantile-quantile plots. The presence of heteroscedasticity in each GEE model was evaluated using the Breusch-Pagan test and by visually inspecting the residuals plot. Marginal R^2 following the methodology of Hardin and Hilbe [16] was computed to enhance the interpretability of the findings. All analyses were performed using R and R Studio (version, 4.3.2). GEE was calculated using the “geepack” package, version 1.3.9. Heteroscedasticity was assessed using the `lmtest` package, version 0.9–40. Statistical significance was defined for all tests *a priori* at $p < 0.050$.

Results

Demographic characteristics and ergometer test results

The anthropometric and general performance characteristics of all participants are displayed in Table 1.

The incremental ergometer test results of all participants are presented in Table 2.

Table 1: Anthropometric and performance data of the participants clustered by sex.

	Males n=95	Females n=60
Age, years	27.3 ± 5.5	25.5 ± 5.1
Height, m	1.82 ± 5.7	1.68 ± 7.2
Mass, kg	79.7 ± 8.3	64.7 ± 9.2
$\dot{V}\text{O}_{2\text{peak}}$, $\text{mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$	44.8 ± 6.8	40.2 ± 4.2
Peak power, W	278.1 ± 41.1	198.7 ± 34.2
Relative peak power, $\text{W}\cdot\text{kg}^{-1}$	3.5 ± 0.6	3.0 ± 0.6
Squat 1RM, kg	94.6 ± 22.0	64.3 ± 13.2
Relative squat 1RM, $\text{kg}\cdot\text{kg}^{-1}$	1.19 ± 0.27	1.0 ± 0.21

Associations between the load-velocity characteristic and the oxygen cost of cycling

The results of the GEE modelling for the gross oxygen cost and the gross caloric unit cost of cycling are presented in Tables 3 and 4, respectively. The GEE modelling revealed a statistically significant inverse association between the strength indices and the gross oxygen cost of cycling. Marginal R^2 values varied between 0.013 and 0.028 for MPVs and between 0.048 and 0.062 for MPPs. Marginal R^2 for 1RM was 0.059. The negative estimates suggest that higher strength capacity is associated with a lower gross oxygen cost in both males and females. Notably, the highest marginal R^2 was found for MPPs at 50 and 70 % of the 1RM (0.062 and 0.061, respectively). Statistically significant effects were observed for the variable $\dot{V}\text{O}_{2\text{peak}}$. Positive estimates for the variable $\dot{V}\text{O}_{2\text{peak}}$ indicate that higher $\dot{V}\text{O}_{2\text{peak}}$ is associated with increased gross oxygen consumption.

Similarly, a statistically significant inverse association between the strength indices and the gross caloric unit cost of cycling was found. Marginal R^2 values ranged from 0.020 to 0.024 for MPVs and from 0.048 to 0.062 for MPPs. Marginal R^2 for 1RM was 0.091. The negative estimates suggest that higher strength capacity is associated with a lower gross oxygen cost in both males and females. Notably, the highest marginal R^2 was found for MPPs at 30 and 50 % of the 1RM (0.103 and 0.102, respectively). Additionally, $\dot{V}\text{O}_{2\text{peak}}$ was identified as a confounding factor. Positive estimates for the variable $\dot{V}\text{O}_{2\text{peak}}$ indicate that higher $\dot{V}\text{O}_{2\text{peak}}$ is associated with increased gross oxygen consumption.

Discussion

In this study, we investigated the associations between strength indices obtained from load-velocity and load-power profiling and parameters of cycling economy, including

Table 2: Participants incremental ergometer test data clustered by sex and workload.

Intensity	50 W		80 W		110 W		140 W	
	Females n=47	Males	Females n=60	Males n=93	Females n=59	Males n=93	Females	Males n=95
Exercise intensity, % $\dot{V}O_{2peak}$	36.5 ± 5.4	–	47.5 ± 2.8	36.3 ± 5.9	60.6 ± 8.7	45.7 ± 7.0	–	55.1 ± 8.5
Blood lactate concentrations, mmol·L ⁻¹	1.1 ± 0.5	–	1.5 ± 0.7	1.1 ± 0.5	2.5 ± 1.1	1.4 ± 0.6	–	2.1 ± 1.0
Gross oxygen cost of cycling, mL·min ⁻¹ ·kg ⁻¹	14.3 ± 2.1	–	19.0 ± 2.8	15.9 ± 1.9	24.3 ± 3.2	20.2 ± 2.4	–	24.3 ± 2.8
Gross caloric unit cost of cycling, kcal·min ⁻¹ ·kg ⁻¹	0.06 ± 0.008	–	0.07 ± 0.010	0.06 ± 0.010	0.10 ± 0.012	0.08 ± 0.010	–	0.10 ± 0.011

Table 3: Generalized estimating equations illustrating the effects of predictors (i.e. MPV, MPP and 1RM, as well as $\dot{V}O_{2peak}$) on the oxygen cost of cycling (mL·min⁻¹·kg⁻¹). Final model used: *Gross oxygen cost* ~ *MPV/MPP/1RM* + $\dot{V}O_{2peak}$. The left panel (strength indices) presents the estimates and marginal R² for the strength index (i.e. MPV, MPP and 1RM) controlled for $\dot{V}O_{2peak}$, while the right panel ($\dot{V}O_{2peak}$) displays the marginal R² value for $\dot{V}O_{2peak}$.

Gross oxygen cost									
Strength indices						$\dot{V}O_{2peak}$			
Predictor	Estimate	Std.Err	Wald Pr.	p-Value	Marginal R ²	Estimate	Std.Err	p-Value	Marginal R ²
MPV 30 %	–2.004	0.838	5.71	0.017	0.013	0.193	0.019	<0.001	0.211
MPV 50 %	–2.500	0.929	7.2	0.007	0.016	0.192	0.019	<0.001	0.209
MPV 70 %	–2.484	0.698	12.7	<0.001	0.028	0.187	0.018	<0.001	0.205
MPV 90 %	–0.154	0.725	0.04	0.830	0.000	0.182	0.018	<0.001	0.207
MPP 30 %	–0.005	0.001	36.3	<0.001	0.055	0.196	0.021	<0.001	0.179
MPP 50 %	–0.005	0.001	28.9	<0.001	0.062	0.199	0.022	<0.001	0.172
MPP 70 %	–0.006	0.001	28.3	<0.001	0.061	0.199	0.022	<0.001	0.172
MPP 90 %	–0.008	0.002	21.9	<0.001	0.048	0.194	0.021	<0.001	0.179
1RM	–0.033	0.006	27.3	<0.001	0.059	0.190	0.020	<0.001	0.179

MPV, mean propulsive velocity; MPP, mean propulsive power; 1RM, one-repetition maximum; Std.Err, standard error; $\dot{V}O_{2peak}$, peak oxygen consumption. Bold values indicate a statistically significant association with $p \leq 0.050$.

Table 4: Generalized estimating equations illustrating the effects of predictors (i.e. MPV, MPP and 1RM, as well as $\dot{V}O_{2peak}$) on the caloric cost of cycling (kcal·min⁻¹·kg⁻¹). Final model used: *Gross caloric unit cost* ~ *MPV/MPP/1RM* + $\dot{V}O_{2peak}$. The left panel (strength indices) presents the estimates and marginal R² for the strength index (i.e. MPV, MPP and 1RM) controlled for $\dot{V}O_{2peak}$, while the right panel ($\dot{V}O_{2peak}$) displays the marginal R² value for $\dot{V}O_{2peak}$.

Gross caloric unit cost									
Strength indices						$\dot{V}O_{2peak}$			
Predictor	Estimate	Std.Err	Wald Pr.	p-Value	Marginal R ²	Estimate	Std.Err	p-Value	Marginal R ²
MPV 30 %	–9.90e-3	3.22e-3	9.48	0.002	0.022	7.82e-4	7.17e-5	<0.001	0.244
MPV 50 %	–1.22e-2	3.46e-3	12.6	<0.001	0.029	7.75e-4	7.18e-5	<0.001	0.239
MPV 70 %	–1.21e-2	2.61e-3	21.3	<0.001	0.049	7.53e-4	7.14e-5	<0.001	0.230
MPV 90 %	9.27e-4	3.27e-3	0.08	0.780	0.000	7.28e-4	6.83e-5	<0.001	0.235
MPP 30 %	–2.42e-5	3.56e-6	46.3	<0.001	0.103	7.98e-4	7.87e-5	<0.001	0.215
MPP 50 %	–2.39e-5	3.53e-6	45.7	<0.001	0.102	8.00e-4	7.98e-5	<0.001	0.211
MPP 70 %	7.92e-4	7.90e-5	40.3	<0.001	0.091	7.92e-4	7.90e-5	<0.001	0.211
MPP 90 %	–3.05e-5	5.97e-6	26.1	<0.001	0.060	7.70e-4	7.53e-5	<0.001	0.218
1RM	–2.55e-5	4.02e-6	40.3	<0.001	0.091	7.92e-4	7.90e-5	<0.001	0.211

MPV, mean propulsive velocity; MPP, mean propulsive power; 1RM, one-repetition maximum; Std.Err, standard error; $\dot{V}O_{2peak}$, peak oxygen consumption. Bold values indicate a statistically significant association with $p \leq 0.050$.

gross oxygen cost and gross caloric unit cost, in recreationally active healthy males and females. We found a statistically significant inverse relationship of strength indices with both gross oxygen cost and gross caloric unit cost. Marginal

R² ranged between 0.013 and 0.062 for the gross oxygen cost and between 0.022 and 0.103 for the gross caloric unit cost, respectively. Additionally, we identified $\dot{V}O_{2peak}$ as a confounding factor, affecting cycling economy.

Our findings indicate that in recreationally active adult males and females, greater 1RM and MPV/MPP, obtained from load-velocity and load-power relationships, affects the gross oxygen cost and gross caloric unit cost of cycling at submaximal intensities. This is in line with other studies performed in healthy males and females, showing that in walking/running greater maximal isometric leg extensor strength is associated with improved movement economy [9]. Although the marginal R^2 values indicate a weak relationship between strength capacity and gross oxygen cost as well as gross caloric cost, accounting for only up to 6 and 10 % of the variance, respectively, these findings are consistent with previous reports [9]. This suggests that the extent to which strength contributes to cycling economy is comparable to its contribution in walking and running. In contrast to walking/running economy, the mechanisms behind the improved cycling economy are still unknown. Unfortunately, the majority of evidence regarding the cycling economy is derived from studies involving athletes that engaged in strength training in order to improve athletic performance [17, 18]. These longitudinal training studies have shown that improved maximal and explosive strength led to altered muscle fiber recruitment patterns toward a more oxidative fiber type [19, 20] and delayed activation of less efficient Type II muscle fibers [8]. However, this differs from the present study, where we analysed the cross-sectional associations between the strength capacity and the cycling economy in recreationally active individuals.

Nonetheless, our data indicate that in recreationally active males and females a greater 1RM strength and higher MPV/MPP are associated with better cycling economy. While the exact mechanisms for this association remain unknown, some evidence from athletic populations points toward shorter contraction times and consequently a reduced time to achieve peak power in each pedal stroke [18]. This in turn may enhance oxygen supply by minimizing periods of restricted blood flow. Indeed, this potential mechanism is similar to walking and running, where it was shown that improved economy in males may result from longer relaxation periods within each gait cycle, leading to better muscular recovery, perfusion, and oxygen transport [21, 22]. Additionally, previous studies showed that factors contributing to enhanced walking/running economy also include neuromuscular mechanisms like improved joint stiffness and intramuscular coordination [23], but also mechanical and morphological properties of the muscle-tendon units may explain variations in running economy [24]. Interestingly, previous studies indicated a stronger association between movement economy and explosive strength, such as higher rates of force development (RFD) [10, 25] and greater contraction velocities [22], compared to maximal strength.

This is in contrast to our findings, where both maximal (i.e. 1RM) and explosive strength (MPV/MPP) were similarly associated with greater cycling economy across the entire load spectrum (i.e. 30–90 % 1RM). This may be attributed to the interconnected nature of maximal and explosive strength, which share physiological and neuromuscular characteristics [26]. This is particularly true when using load-velocity relationships as indicators of strength performance, where the movement velocity is directly linked to the executed load [27].

Importantly, our data revealed $\dot{V}O_{2peak}$ as a confounding factor for the observed associations, as participants with a lower $\dot{V}O_{2peak}$ showed a greater exercise economy. This finding is well in line with observations in elite cyclists [28]. In the specific population of elite athletes, it appears that lower $\dot{V}O_{2max}/\dot{V}O_{2peak}$ is compensated by a greater cycling economy/efficiency [28]. However, it is somewhat surprising that in the present study with healthy but untrained individuals $\dot{V}O_{2peak}$ was inversely related to cycling economy, especially since typically a higher $\dot{V}O_{2peak}$ indicates better cardiovascular fitness and aerobic capacity [29]. These traits commonly reflect a more aerobic phenotype, which would generally be expected to correlate with better economy [7]. However, a higher $\dot{V}O_{2peak}$ implies a greater ability to produce energy aerobically as well, which affects substrate metabolism [30]. Notably, marginal R^2 presented in this study were comparable for both gross oxygen and gross caloric unit cost, suggesting that the impact of greater strength capacity on cycling economy in this specific population seems to be independent of substrate metabolism. Importantly, substrate metabolism may account for a significant portion of the observed variance as individuals with higher oxidative capacity are likely to exhibit greater fat metabolism [31], requiring a higher $\dot{V}O_2$. However, this may be negligible in a population not specifically endurance-trained, as fat metabolism is only moderately developed [32]. However, apart from metabolic factors that may explain why greater $\dot{V}O_{2peak}$ is associated with lower cycling economy, higher submaximal oxygen consumption can also arise from higher basal metabolic rates [33, 34] and mechanical and morphological properties of the muscle-tendon unit [35], which may aid in explaining the observed inverse relationship.

Despite the differences between highly adapted athletes and untrained but healthy individuals, the associations between strength capacity and cycling economy appear to be comparable. Even though we assessed cross-sectional associations between strength capacity and cycling economy our data may suggest that prolonged, systematic strength training could potentially enhance cycling economy in untrained individuals, as demonstrated in numerous training studies with athletes [7, 8, 36–38].

Although we expand the evidence on the relationship of cycling economy and strength capacity, this study has limitations. We evaluated the cycling economy using a step protocol, which allows to analyse various submaximal workloads. Consequently, we had to use a fixed workload (50 W, 80 W, and 110 W in females & 80 W, 110 W, and 140 W in males) leading to heterogenous exercise intensities ranging from $36.5 \pm 5.4\%$ to $60.6 \pm 8.7\%$ of $\dot{V}O_{2\text{peak}}$ in females and $45.7 \pm 7.0\%$ to $55.1 \pm 8.5\%$ of $\dot{V}O_{2\text{peak}}$ in males, respectively. However, we did not analyse each workload separately but much rather used GEE models for our analysis.

Conclusions

Our findings indicate that load-velocity and load-power characteristics are associated with reduced gross oxygen cost as well as gross caloric unit cost during submaximal cycling in healthy but recreationally active males and females. While these findings are in line with previous studies, this relationship explains only a small proportion of the observed variation, accounting for 1.3–6.2 % of the variance in gross oxygen cost and 2.2–10.3 % of the variance in gross caloric unit cost. This emphasizes the significance of both maximal and explosive strength capacity in facilitating cycling at lower oxygen and caloric demands. Future studies should assess whether this promotes a more efficient and sustainable physical activity level as represented by a better adherence to physical activity guidelines.

Research ethics: The study was conducted in accordance with the Declaration of Helsinki.

Informed consent: Informed consent was obtained from all individuals included in this study, or their legal guardians or wards.

Author contributions: The authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Competing interests: The authors declare that they have no competing interests.

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Data availability: Data is available upon reasonable request.

References

1. Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. *Med Sci Sports Exerc* 2000;32:70–84.
2. Vanhees L, Geladas N, Hansen D, Kouidi E, Niebauer J, Reiner Ž, et al. Importance of characteristics and modalities of physical activity and exercise in the management of cardiovascular health in individuals with cardiovascular risk factors: recommendations from the EACPR (part II). *Eur J Prev Cardiol* 2012;19:1005–33.
3. Vikmoen O, Ellefsen S, Trøen Ø, Hollan I, Hanestadhaugen M, Raastad T, et al. Strength training improves cycling performance, fractional utilization of $\dot{V}O_{2\text{max}}$ and cycling economy in female cyclists. *Scand J Med Sci Sports* 2016;26:384–96.
4. Sunde A, Støren Ø, Bjerkaas M, Larsen MH, Hoff J, Helgerud J. Maximal strength training improves cycling economy in competitive cyclists. *J Strength Condit Res* 2010;24:2157–65.
5. LaRoche DP, Melanson EL, Baumgartner MP, Bozzuto BM, Libby VM, Marshall BN. Physiological determinants of walking effort in older adults: should they be targets for physical activity intervention? *Geroscience* 2018;40:305–15.
6. Owen N, Healy GN, Matthews CE, Dunstan DW. Too much sitting. *Exerc Sport Sci Rev* 2010;38:105–13.
7. Coyle EF, Sidossis LS, Horowitz JF, Beltz JD. Cycling efficiency is related to the percentage of type I muscle fibers. *Med Sci Sports Exerc* 1992;24:782–8.
8. Rønnestad BR, Mujika I. Optimizing strength training for running and cycling endurance performance: a review. *Scand J Med Sci Sports* 2014;24:603–12.
9. Schumann M, Chen Z, Wang X, Le S, Zhang T, Waller K, et al. Maximal isometric strength indices are associated with the oxygen cost of walking and running in recreationally active men and women. *Res Sports Med* 2022;30:540–53.
10. Hoff J, Tjønnå AE, Steinshamn S, Høydal M, Richardson RS, Helgerud J. Maximal strength training of the legs in COPD. *Med Sci Sports Exerc* 2007;39:220–6.
11. McNulty KL, Elliott-Sale KJ, Dolan E, Swinton PA, Ansdell P, Goodall S, et al. The effects of menstrual cycle phase on exercise performance in eumenorrheic women: a systematic review and meta-analysis. *Sports Med* 2020;50:1813–27.
12. Jeukendrup AE, Wallis GA. Measurement of substrate oxidation during exercise by means of gas exchange measurements. *Int J Sports Med* 2005;26:28–37.
13. González-Badillo JJ, Sánchez-Medina L. Movement velocity as a measure of loading intensity in resistance training. *Int J Sports Med* 2010;31:347–52.
14. Poole DC, Jones AM. Oxygen uptake kinetics. *Compr Physiol* 2012:933–96.
15. Pate RR, Macera CA, Bailey SP, Bartoli WP, Powell KE. Physiological, anthropometric, and training correlates of running economy. *Med Sci Sports Exerc* 1992;24:1128–33.
16. Hardin JW, Hilbe JM. Generalized estimating equations. In: Agostino RBD, Sullivan L, Massaro J, editors. *Wiley encyclopedia of clinical trials*. John Wiley & Sons, Inc; 2007, vol 135:1370–8378 pp.
17. Aagaard P, Andersen JL. Effects of strength training on endurance capacity in top-level endurance athletes. *Scand J Med Sci Sports* 2010;20:39–47.
18. Rønnestad BR, Hansen J, Hollan I, Ellefsen S. Strength training improves performance and pedaling characteristics in elite cyclists. *Scand J Med Sci Sports* 2015;25:e89–98.
19. Aagaard P, Andersen JL, Bennekou M, Larsson B, Olesen JL, Crameri R, et al. Effects of resistance training on endurance capacity and muscle fiber composition in young top-level cyclists. *Scand J Med Sci Sports* 2011;21:e298–307.
20. Vikmoen O, Raastad T, Seynnes O, Bergstrøm K, Ellefsen S, Rønnestad BR. Effects of heavy strength training on running

- performance and determinants of running performance in female endurance athletes. *PLoS One* 2016;11:e0150799.
21. Richardson RS, Harms CA, Grassi B, Hepple RT. Skeletal muscle: master or slave of the cardiovascular system? *Med Sci Sports Exerc* 2000;89. <https://doi.org/10.1097/00005768-200001000-00014>.
 22. Østerås H, Helgerud J, Hoff J. Maximal strength-training effects on force-velocity and force-power relationships explain increases in aerobic performance in humans. *Eur J Appl Physiol* 2002;88: 255–63.
 23. Perrault H. Efficiency of movement in health and chronic disease. *Clin Invest Med* 2006;29:117–21.
 24. Arampatzis A, De Monte G, Karamanidis K, Morey-Klapsing G, Stafilidis S, Brüggemann GP. Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. *J Exp Biol* 2006;209:3345–57.
 25. Karlsen T, Helgerud J, Støylen A, Lauritsen N, Hoff J. Maximal strength training restores walking mechanical efficiency in heart patients. *Int J Sports Med* 2009;30:337–42.
 26. Cormie P, McGuigan MR, Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Med Sci Sports Exerc* 2010;42:1566–81.
 27. González-Badillo J, Marques M, Sánchez-Medina L. The importance of movement velocity as a measure to control resistance training intensity. *J Hum Kinet* 2011;29A:15–9.
 28. Lucia A, Hoyos J, Pérez M, Santalla A, Chicharro JL. Inverse relationship between VO₂max and economy/efficiency in world-class cyclists. *Med Sci Sports Exerc* 2002;43:2079–84.
 29. Jones AM, Carter H. The effect of endurance training on parameters of aerobic fitness. *Sports Med* 2000;29:373–86.
 30. Purdom T, Kravitz L, Dokladny K, Mermier C. Understanding the factors that effect maximal fat oxidation. *J Int Soc Sports Nutr* 2018;15. <https://doi.org/10.1186/s12970-018-0207-1>.
 31. Lima-Silva AE, Bertuzzi RCM, Pires FO, Gagliardi JFL, Barros RV, Hammond J, et al. Relationship between training status and maximal fat oxidation rate. *J Sports Sci Med* 2010;9:31–5.
 32. Klein S, Coyle EF, Wolfe RR. Fat metabolism during low-intensity exercise in endurance-trained and untrained men. *Am J Physiol Endocrinol Metabol* 1994;267:E934–40.
 33. Ando T, Piaggi P, Bogardus C, Krakoff J. VO_{2max} is associated with measures of energy expenditure in sedentary condition but does not predict weight change. *Metabolism* 2019;90:44–51.
 34. Ettema G, Lorås HW. Efficiency in cycling: a review. *Eur J Appl Physiol* 2009;106:1–14.
 35. Rønnestad BR, Hansen EA, Raastad T. Strength training affects tendon cross-sectional area and freely chosen cadence differently in noncyclists and well-trained cyclists. *J Strength Condit Res* 2012;26: 158–66.
 36. Balsalobre-Fernández C, Santos-Concejero J, Grivas GV. Effects of strength training on running economy in highly trained runners: a systematic review with meta-analysis of controlled trials. *J Strength Condit Res* 2016;30:2361–8.
 37. Trowell D, Vicenzino B, Saunders N, Fox A, Bonacci J. Effect of strength training on biomechanical and neuromuscular variables in distance runners: a systematic review and meta-analysis. *Sports Med* 2020;50: 133–50.
 38. Blagrove RC, Howatson G, Hayes PR. Effects of strength training on the physiological determinants of middle- and long-distance running performance: a systematic review. *Sports Med* 2018;48:1117–49.