Check for updates

Scandinavian Journal of Medicine & Science in Sports

WILEY

ORIGINAL ARTICLE OPEN ACCESS

Low-Rate Carbohydrate Ingestion Mitigates the Loss of Power Output at the Moderate-To-Heavy Intensity Transition During Prolonged Cycling

Enea Iten[1,2] | Andrew E. Kilding[2,3] | Daniel J. Plews[2,3] | Ed Maunder[2,3]

[1]Exercise Physiology Lab, Institute of Human Movement Sciences and Sport, ETH Zurich, Zurich, Switzerland | [2]AUT Sports Research Institute New Zealand, Auckland University of Technology, Auckland, New Zealand | [3]School of Sport, Exercise, and Health, Auckland University of Technology, Auckland, New Zealand

Correspondence: Ed Maunder (ed.maunder@aut.ac.nz)

Received: 2 June 2026 | **Revised:** 2 November 2026 | **Accepted:** 4 November 2026

ABSTRACT

We investigated whether a low carbohydrate ingestion rate during prolonged cycling improves durability and maintains blood glucose concentration. Thirteen trained cyclists and triathletes ($\dot{V}O_2$peak: 57.1 ± 7.6 mL·kg^{-1}·min^{-1}) completed a randomized, single-blind, crossover study including assessment of the intensity domain transitions in three conditions: without prior cycling (FRESH), following prolonged cycling with 15 g·h^{-1} carbohydrate ingestion (CHO), and following prolonged cycling with placebo ingestion (PLA). Prolonged trials consisted of 150 min of cycling at 90% of the power output associated with the estimated first ventilatory threshold (VT_1). The moderate-to-heavy (power output at VT1) and heavy-to-severe (critical power) intensity transitions were assessed via a submaximal incremental test and a three-minute all-out test, respectively. Power output at VT_1 was significantly lower in PLA (176 ± 47 W) than FRESH (193 ± 56 W; $p = 0.003$) and CHO (189 ± 55 W; $p = 0.047$), with no difference between CHO and FRESH. Exploratory comparisons at individual timepoints showed blood glucose concentration was higher in CHO than PLA at 30 and 90 min, and prior to the incremental test (5.5 ± 0.5 vs. 4.7 ± 0.3 mmol·L^{-1}; $p = 0.0008$). Critical power was higher in FRESH than PLA (312 ± 72 vs. 298 ± 67 W; $p = 0.049$), with no differences between CHO and PLA. These findings indicate that carbohydrate ingestion at 15 g·h^{-1} during prolonged cycling attenuates the decline in power output at VT_1, and may be associated with improved maintenance of blood glucose concentrations.

1 | Introduction

Physiological responses to prolonged exercise can be grouped into discrete moderate, heavy, and severe intensity domains, characterized by rapid, delayed, and failure to achieve a metabolic steady state, respectively [1]. Power outputs at the intensity domain transitions are key determinants of endurance performance [2] and are used in training load monitoring and programming [3–5]. Recent experimental studies have observed a reduction in power output at the moderate-to-heavy [6–9] and heavy-to-severe [10, 11] intensity transitions during prolonged exercise. An individual's resilience to the effects of prolonged exercise on power output at the intensity domain transitions has been termed "durability" [4]. Durability has implications for training load monitoring and performance [3, 4].

The mechanisms that underpin durability have not been established. Carbohydrate ingestion at 60 g·h^{-1} mitigates the reduction in power output at the intensity domain transitions during prolonged cycling [12–14], and it is well established that carbohydrate ingestion during prolonged exercise extends exercise capacity and improves endurance performance [15]. Carbohydrates ingested during exercise are absorbed across the intestine and transported to working skeletal muscle for

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *Scandinavian Journal of Medicine & Science In Sports* published by John Wiley & Sons Ltd.

oxidation [16]. Exogenous carbohydrate oxidation rates can increase up to ingestion rates of ~90–120 g·h^{-1} when carbohydrates are ingested from multiple sources that utilize different intestinal transport mechanisms [17]. Exogenous carbohydrate oxidation reduces endogenous carbohydrate and fat oxidation in an approximately 1:1 ratio [18], with much of the reduction in endogenous carbohydrate oxidation attributable to reduced liver glycogen utilization [19], although a small reduction in muscle glycogen utilization may also occur [20]. Therefore, it has long been posited that carbohydrate ingestion during exercise improves performance via slowed glycogen depletion [21, 22]. Sports nutrition guidelines recommend carbohydrate ingestion at rates of ~30–60 g·h^{-1} during prolonged exercise of shorter duration, with intakes of up to ~90 g·h^{-1} (and, in more recent practice, sometimes higher) recommended for longer events when multiple transportable carbohydrates are ingested, to reduce endogenous carbohydrate oxidation [23].

Carbohydrate ingestion also delays or mitigates exercise-induced reductions in blood glucose concentration [13, 15]. Therefore, the durability-enhancing effects of carbohydrate ingestion during prolonged exercise may be at least partially explained by improved maintenance of blood glucose concentrations. Maintenance of euglycaemia appears to preserve central nervous system activation, while carbohydrate ingestion attenuates central and peripheral neuromuscular fatigue [24, 25]. Therefore, prolonged exercise-induced reductions in blood glucose concentrations may contribute to fatigue via impaired central nervous system function [25, 26]. Given that the total glucose present in the circulation is relatively small (~4 g) [27, 28], modest ingestion rates may be sufficient to stabilize glycaemia [29]. Therefore, investigation of low carbohydrate ingestion rates during prolonged exercise will improve our understanding of durability and has implications for training stress management and performance. Studying the effects of low carbohydrate ingestion rates on durability is further warranted by recent research reporting carbohydrate ingestion at ~10 g·h^{-1} extends prolonged exercise capacity [30].

The aim of this study was to determine: (1) if a low carbohydrate ingestion rate (15 g·h^{-1}) during prolonged cycling improves durability; and (2) if 15 g·h^{-1} of carbohydrate ingestion is sufficient to maintain blood glucose concentrations during prolonged cycling. We hypothesized that 15 g·h^{-1} of carbohydrate ingestion during prolonged cycling would improve durability of the intensity domain transitions and be sufficient to maintain blood glucose concentrations.

2 | Methods

2.1 | Participants

Thirteen trained cyclists (seven) and triathletes (six) were recruited to take part in this investigation (nine males, four females; age, 30 ± 8 years; height, 174.5 ± 9.8 cm; mass, 71.1 ± 11.9 kg; peak oxygen uptake [$\dot{V}O_2$peak], 57.1 ± 7.6 mL·kg^{-1}·min^{-1}; training volume, 10 ± 2 h·week^{-1}). The participants ranged from 20 to 42 years old, were free of illness and musculoskeletal injury (> 3 months), had never had cardiovascular disease, self-reported training > 8 h·week^{-1}, and had $\dot{V}O_2$peak > 50 mL·kg^{-1}·min^{-1} for males and > 42 mL·kg^{-1}·min^{-1} for females (determined in the first visit) and a self-reported best-effort 20-min power output of > 3.5 W·kg^{-1} in males and > 3.0 W·kg^{-1} in females (Table 1). Menstrual cycle phase was not controlled in this study based on recent evidence that the power-duration relationship and heavy-to-severe intensity transition is equally reproducible in eumenorrheic females and males [31]. A priori sample size estimation indicated a total of 12 participants were required to detect a large magnitude (d = 0.8) effect of carbohydrate ingestion on our primary outcome measure, durability of the moderate-to-heavy intensity transition, with 80% power and a Type I error rate of 0.05, using a one-tailed test (G*Power, 3.1). A large effect size and one-tailed test were used as previous research on the effect of carbohydrate ingestion during exercise on durability of the moderate-to-heavy transition reported a large effect [13]. All participants completed a general health screening and provided written informed consent. This study was performed in accordance with the standards of the Declaration of Helsinki, 2013, and the Auckland University of Technology Ethics Committee approved all procedures (23/197).

2.2 | Study Design

This study involved four laboratory visits and employed a randomized, Latin square counterbalanced, single-blind crossover design, including one characterization trial and three experimental trials (Figure 1). The first visit was used to assess eligibility, determine power output at the first ventilatory threshold (VT_1) and peak oxygen uptake ($\dot{V}O_2$peak), peak fat oxidation (PFO), and gross cycling efficiency, and familiarize participants with the 3-min all-out test (3MAOT) used in subsequent trials. Visits 2–4 consisted of the experimental trials and were conducted in a randomized, counterbalanced order. Each experimental trial began in the morning following the consumption of a breakfast containing ~2 g·kg^{-1} of carbohydrate and ~800 mL of water, and involved measurement of VT_1 using a five-step incremental test and critical power using a 3MAOT (i) without prior cycling (FRESH), (ii) following 150 min of cycling at 90% of the initial estimate of VT_1, with consumption of a carbohydrate solution consisting of 50% maltodextrins and 50% glucose at 15 g·h^{-1} (CHO), and (iii) following 150 min of cycling at 90% of the initial estimate of VT_1,

TABLE 1 | Descriptive participant characteristics.

	Female (n = 4)	Male (n = 9)
Age (years)	22 ± 2	33 ± 8
Training volume (h/week)	9.8 ± 2.1	10.1 ± 1.6
Height (cm)	164 ± 7	179 ± 7
Mass (kg)	57 ± 8	77 ± 7
$\dot{V}O_2$peak (mL/kg/min)	54 ± 5	59 ± 8
P$\dot{V}O_2$peak (W)	283 ± 32	413 ± 51
PVT_1 (W)	140 ± 32	215 ± 38

Abbreviations: P$\dot{V}O_2$peak = power at $\dot{V}O_2$peak, PVT_1 = power at first ventilatory threshold.

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

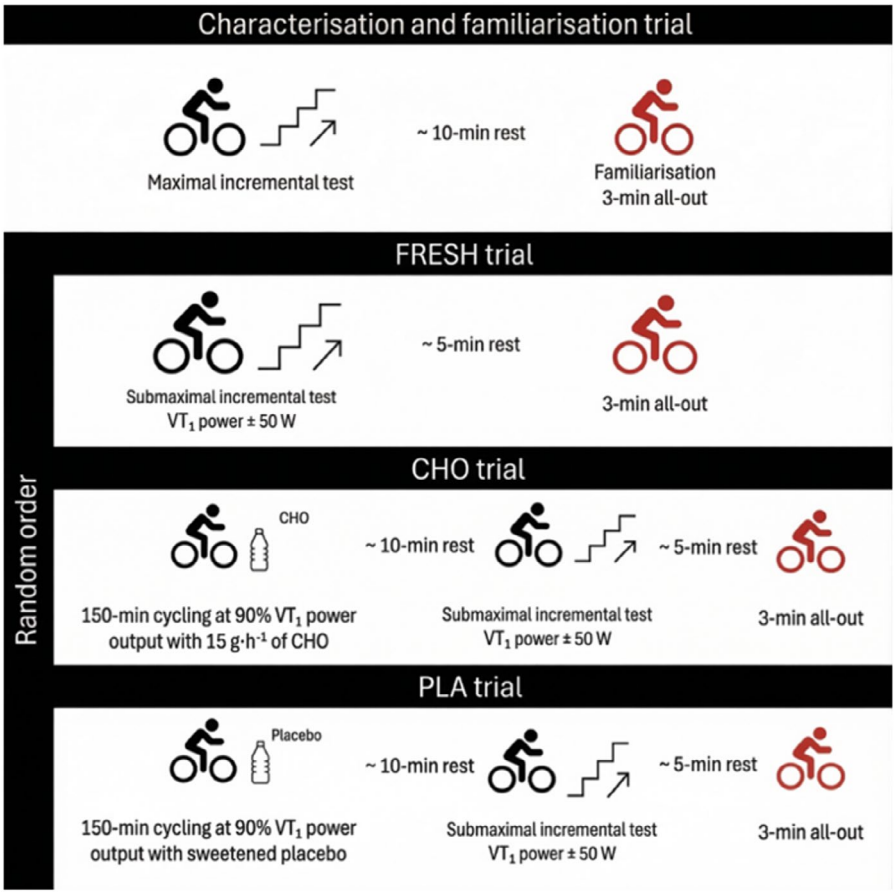

FIGURE 1 | Schematic overview of the study design. VT_1, first ventilatory threshold; CHO, carbohydrate.

without carbohydrate (PLA). In PLA, participants consumed a calorie-free, taste-matched placebo drink. Participants were blinded to the condition (CHO vs. PLA). Power output at VT_1 was used as an estimate of the moderate-to-heavy-intensity transition [8], and the mean power output in the last 30-s of the 3MAOT was used as an estimate of the heavy-to-severe intensity transition [32].

2.3 | Characterization Trial

Participants arrived in the laboratory having fasted overnight for ~10 h and having ingested ~1–2 L of water in the morning before arrival. All exercise testing was conducted in a well-ventilated laboratory at a temperature of 18°C–20°C. Before beginning the session, the height and body mass of participants were measured (Harpenden, Holtain Ltd., Crymych, UK; HW-200KGL, Weightec Ltd., Auckland, NZ). Cycling then commenced on an electronically braked cycle ergometer (Lode Excalibur Sport, Lode, Groningen, Netherlands) at 95 W for males and 60 W for females. The work rate increased by 35 W every 3 min. Ratings of perceived exertion (RPE) were recorded using the Borg 6–20 scale, 30 s before the end of each stage. Expired gases and heart rate were collected continuously during exercise (Quark CPET, Cosmed, Rome, Italy; Polar H10, Polar Electro Oy, Kempele, Finland). Once the respiratory exchange ratio (RER) reached >1.0 and an RPE ≥ 15, the work rate was increased by 35 W per minute until volitional exhaustion. The $\dot{V}O_2$peak was accepted as the highest 15-s average $\dot{V}O_2$. The VT_1 was determined by visual inspection as the $\dot{V}O_2$ at the first breakpoint in the $\dot{V}O_2$ vs. $\dot{V}_E{\cdot}\dot{V}O_2{}^{-1}$ relationship, without additional ventilatory equivalents or end-tidal criteria. Two independent raters identified $\dot{V}O_2$ at VT_1 and the arithmetic mean was used when the difference between raters was $<10\%$. If the estimated values differed by $\geq 10\%$, this was resolved by consensus. Raters were blinded to trial when estimating $\dot{V}O_2$ at VT_1. This $\dot{V}O_2$ was subsequently converted into a power output via simple linear regression of $\dot{V}O_2$ vs. power output during the 3-min stages, using the average $\dot{V}O_2$ in the last minute of each stage. The last minute of expired gas data in each 3-min stage was used to quantify whole-body fat oxidation using standard equations [33] (Equation 1):

$$\begin{aligned}\text{Energy expenditure}\left(\text{kcal}\cdot\text{min}^{-1}\right)&=0.550\times\text{VCO}_2+4.471\times\text{VO}_2\\ \text{Fat oxidation rate}\left(\text{g}\cdot\text{min}^{-1}\right)&=1.695\times\dot{V}O_2-1.701\times\dot{V}CO_2\\ \text{CHO oxidation rate}\left(\text{g}\cdot\text{min}^{-1}\right)&=4.210\times\dot{V}CO_2-2.962\times\dot{V}O_2\end{aligned}\quad(1)$$

where $\dot{V}O_2$ and $\dot{V}CO_2$ are in $L{\cdot}min^{-1}$.

After completion of the incremental test, participants rested for ~10 min, followed by a 5-min warm-up at 100 W for males and 75 W for females before completing a 3MAOT. Participants were instructed to perform the 3MAOT at maximal effort from the onset, without employing any pacing strategy. They were blinded to power output, heart rate, cadence, and elapsed time. To perform the 3MAOT, a linear factor was calculated for each participant. The power output corresponding to 50% of the difference

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

between the power output at VT_1 and that at $\dot{V}O_2$peak, together with the self-selected cadence, was used to determine the linear factor according to the following equation [34]:

$$\text{Linear factor} = \frac{PVT_1 + P\dot{V}O_2\text{peak}}{2 \times \text{cadence}^2} \quad (2)$$

where P is power output expressed in W and cadence in rpm.

2.4 | Experimental Trials

Participants were instructed to replicate, as closely as possible, the dietary intake and physical training (in terms of volume and intensity) undertaken during the 3 days preceding the characterization trial in the 3 days preceding each of the three experimental trials. Diet and training were recorded and replication was reviewed by the researchers. Participants returned to the laboratory 5–14 days later to complete the first of the three experimental trials. Participants arrived having consumed a breakfast of their choosing containing ~2 g·kg^{-1} of carbohydrate, which was replicated for all experimental trials, and ~800 mL of water 1 h beforehand, and having refrained from caffeine and alcohol consumption for 24 h. Participants were fitted with a heart rate monitor such that heart rate was recorded continuously throughout the trial. All trials began with a 5-min warm-up at 100 W for males and 75 W for females. Following the warm-up, participants cycled for 150 min at 90% of the VT_1 power output estimated in the characterization trial in the CHO and PLA trials, but not the FRESH trial, with expired gases collected for 4 min every 15 min. Expired gas data were used to quantify rates of whole-body energy expenditure, carbohydrate oxidation, and fat oxidation during the 150-min preload. During the CHO and PLA trials, participants consumed 150 mL of water every 20 min. As the last scheduled drink was after 140 min, a further 75 mL was provided at the end of the prolonged phase of the trial (i.e., after 150 min). In CHO, water was mixed with a calorie-free electrolyte mix (Electrolytes, Musashi, Vitaco Health, Auckland, New Zealand) and a mix of 50% glucose and 50% maltodextrin (Carbs, Switch Nutrition, Maroochydore QLD, Australia) such that carbohydrate was consumed at a rate of 15 g·h^{-1} during the 150-min preload. In total, 37.5 g of carbohydrate was ingested in CHO (5 g every 20 min, and a further 2.5 g at 150 min). In PLA, water was mixed with the same calorie-free electrolyte mix. Taste was matched across conditions, as flavor was provided by the electrolyte mix, whereas the glucose–maltodextrin mixture was unflavoured. Additionally, fingertip capillary blood samples were collected at rest and every 30 min during the 150-min preload using a blood glucose analyzer (Caresens N Premier, i-SENS Inc., Seoul, Republic of Korea) in CHO and PLA. Blood glucose was measured again at rest, approximately 10 min after the end of the 150-min preload and immediately before the five-stage incremental test. Blood glucose total area under the curve (AUC) was calculated for each participant using the trapezoidal rule on raw concentrations from 0 to 150 min (six samples, every 30 min) and expressed in mmol·L^{-1}·min. Participants were blinded to the trial condition (CHO or PLA), whereas the test personnel were not blinded.

Subsequently, the moderate-to-heavy in g a five-step incremental test, with continuous collection of expired gases. The test commenced after a 5-min warm-up performed at 100 W for males and 75 W for females. The first step was set at 50 W below the VT_1 power output determined during the first laboratory visit, with power output increasing by 25 W every 4 min, such that the fifth and final step was 50 W above VT_1. The moderate-to-heavy intensity transition power output was obtained using the methods previously described for determining VT_1 in the first laboratory visit, but with greater precision given the denser cluster of datapoints around the transition. The average VO_2, derived from the interpolation of two data points provided by two independent raters (the same two for each trial) blinded to condition, was used to estimate power at VT_1 via linear regression. Between-rater reliability of VT_1 determination was high for $\dot{V}O_2$ (ICC(2, k) = 0.984, two-way random, absolute agreement, mean of two raters; typical error = 107 mL·min^{-1}; coefficient of variation of ~4.1%) and for the corresponding power output (ICC(2, k) = 0.982; typical error = 10.0 W; coefficient of variation of ~5.4%). On the two occasions in which estimates varied by > 10% between raters, the two independent raters reassessed the plot together until agreement was reached. These indices reflect agreement between raters, not day-to-day reproducibility, which was not assessed. The five-step incremental test was performed under fresh conditions following the same protocol.

The mechanical power output achieved at an intensity domain transition is, mathematically, determined by the rate of metabolic energy expenditure achieved at the transition (here termed "metabolic power") and the efficiency of conversion of metabolic energy expenditure to mechanical power output (here termed "metabolic efficiency"). We therefore used a mathematical model to quantify the proportion of between-trial differences in power output at the intensity domain transitions attributable to changes in metabolic efficiency and metabolic power. To do this, we first estimated metabolic power at VT_1 by linear regression of the mechanical power output (W) vs. metabolic energy expenditure (kcal·min^{-1}) relationship in PLA and CHO. We then used metabolic power at VT_1 in PLA and CHO to estimate the power output at the transitions that would be achieved with the metabolic efficiency in FRESH (here termed "$CHO_{Power}FRESH_{Eff}$" and "$PLA_{Power}FRESH_{Eff}$"). To estimate $CHO_{Power}FRESH_{Eff}$ and $PLA_{Power}FRESH_{Eff}$, we converted metabolic power in PLA and CHO (kcal·min^{-1}) to mechanical power output using linear regression of the mechanical power output (W) vs. metabolic energy expenditure (kcal·min^{-1}) relationship in FRESH. Accordingly, the proportion of PLA/CHO-induced changes in power output at the intensity domain transitions attributable to changes in metabolic efficiency and metabolic power was calculated using the below equations (Eq 3). These calculations have been used previously [8, 13, 35]:

$$\begin{aligned}&\text{Contribution of metabolic power to between-trial}\\&\quad\text{difference (CHO vs. FRESH) in power output}\\&\quad\text{at the intensity domain transition}\\&\quad= CHO_{Power}FRESH_{Eff} - FRESH\end{aligned}$$

$$\begin{aligned}&\text{Contribution of metabolic power to between-trial}\\&\quad\text{difference (PLA vs. FRESH) in power output}\\&\quad\text{at the intensity domain transition}\\&\quad= PLA_{Power}FRESH_{Eff} - FRESH\end{aligned}$$

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

$$\begin{aligned}&\text{Contribution of metabolic efficiency to between-trial}\\&\quad\text{difference (CHO vs. FRESH) in power output}\\&\quad\text{at the intensity domain transition}\\&\quad=\text{CHO}-\text{CHO}_{\text{Power}}\text{FRESH}_{\text{Eff}}\\&\text{Contribution of metabolic efficiency to between-trial}\\&\quad\text{difference (PLA vs. FRESH) in power output}\\&\quad\text{at the intensity domain transition}\\&\quad=\text{PLA}-\text{PLA}_{\text{Power}}\text{FRESH}_{\text{Eff}}\end{aligned}\tag{3}$$

where PLA, CHO, and FRESH represent power outputs at VT_1 under their respective conditions. $CHO_{Power}FRESH_{Eff}$ and $PLA_{Power}FRESH_{Eff}$ are calculated power outputs at VT_1 for CHO and PLA assuming FRESH efficiency.

Following the five-step incremental test, participants rested for 5 min and then cycled at 100 W for 5 min for males and 75 W for females before completing a 3MAOT according to the procedures described in the characterization trial. Critical power (CP) was determined as the mean power over the final 30 s of the 3MAOT, and W′ was calculated as the product of the test duration (180 s) and the difference between the 3MAOT mean power and CP. The 3MAOT was therefore performed after the prolonged cycling preload and the 20-min five-step incremental test. Consequently, CP and W′ reflect the combined effect of the preload and the subsequent incremental exercise, rather than the preload alone.

2.5 | Statistical Analysis

Data were expressed as mean ± standard deviation and analyzed using GraphPad Prism Version 11.0.0. Power output at VT_1, CP, W′, and blood glucose concentration immediately before the five-step incremental test were compared between trials using a repeated measures one-way analysis of variance with trial as factor. Sphericity of the data was not assumed, and when needed, a Geisser–Greenhouse correction was used. Mean and standard deviation within-participant differences were calculated and expressed with 95% confidence intervals where appropriate. Blood glucose concentration during the 150-min preload was assessed using a repeated measures two-way analysis of variance with trial and time as factors. Whole-body rates of energy expenditure, carbohydrate oxidation, fat oxidation, gross efficiency, and heart rate during the 150-min preload in PLA and CHO were compared using mixed-effects analysis due to missing data (heart rate disconnected in two trials and $\dot{V}O_2$ and $\dot{V}CO_2$ calculations were similarly affected in two trials), with trial and time as factors. Šídák's multiple comparisons tests were used to locate significant pairwise differences, and Šídák-adjusted *p*-values are reported. The contributions made by metabolic power and metabolic efficiency to changes in power output at VT_1 in PLA and CHO vs. FRESH were compared between trials using paired *t*-tests (or non-parametric equivalents).

2.6 | Use of Artificial Intelligence Tools

Generative AI tools were used during the preparation of this manuscript, as follows. ChatGPT (OpenAI, version 5.3) was used to generate Python code for data cleaning and data visualization. It was also used throughout the manuscript for language editing (rephrasing and grammar correction) and to translate draft passages written in Italian and English into scientific English. Gemini 2.5 Flash (Google) was used as a second tool to generate Python code for data analysis and visualization. All AI-generated code was reviewed line by the authors, run on the study dataset, and checked by comparing outputs (e.g., descriptive statistics, sample sizes, test results) against manual calculations and independent checks. All text edited or translated with AI was revised by the authors to make sure the scientific content and meaning stayed accurate. The authors take full responsibility for the content and integrity of the manuscript, in line with the journal's policy on the use of AI.

3 | Results

3.1 | Characterization Trial

The $\dot{V}O_2$peak measured in the characterization trial was 4.07 ± 0.88 L·min^{-1} and the associated power output was 373 ± 77 W. The estimated power output at VT_1 was 192 ± 50 W, and thus a power output of 173 ± 45 W was used during the 150 min preload phase of the prolonged trials. The critical power and W′ measured during the characterization trial were 297 ± 64 W and 10.9 ± 5.4 kJ, respectively.

3.2 | Prolonged Phase

There was an effect of time for carbohydrate oxidation, fat oxidation, energy expenditure, gross efficiency, oxygen consumption and minute ventilation, but no effect of trial or interaction between time and trial was significant (Figure 2). During the preload phase, blood glucose concentration showed a significant main effect of time ($p < 0.0001$), with no significant effect of trial ($p = 0.066$) or time × trial interaction ($p = 0.052$). As the glycaemic profile in CHO did not appear linear on visual inspection (Figure 3A), we performed pairwise comparisons ($n = 6$) between CHO and PLA at each sampling timepoint (0, 30, 60, 90, 120, 150 min), corrected for multiplicity using Šídák's multiple comparisons test. Blood glucose concentration was higher in CHO than PLA at 30 min (5.9 ± 0.4 vs. 5.5 ± 0.5 mmol·L^{-1}, Δ 0.5 ± 0.5 [0.2, 0.8] mmol·L^{-1}, $p = 0.0108$) and at 90 min (5.6 ± 0.4 vs. 5.0 ± 0.5 mmol·L^{-1}, Δ 0.6 ± 0.6 [0.2, 1.0] mmol·L^{-1}, $p = 0.0015$). As these timepoints were selected post hoc rather than prespecified, these findings should be interpreted as exploratory. Drinks were ingested every 20 min (starting at $t = 20$ min), whereas blood samples were taken every 30 min, immediately before the drink when the two coincided (at 60 and 120 min). Sampling therefore occurred 10 or 20 min after the most recent drink. The non-linear pattern in blood glucose in CHO may therefore reflect the timing of sampling relative to drink ingestion. The total blood glucose AUC did not differ significantly between conditions (CHO: 819 ± 46 vs. PLA: 774 ± 60 mmol·L^{-1}·min, Δ 45 ± 76 [−1, 91] mmol·L^{-1}·min, paired *t*-test, $p = 0.053$).

3.3 | Five-Step Incremental Test

Blood glucose concentration before the start of the five-step incremental test was significantly higher in FRESH than

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

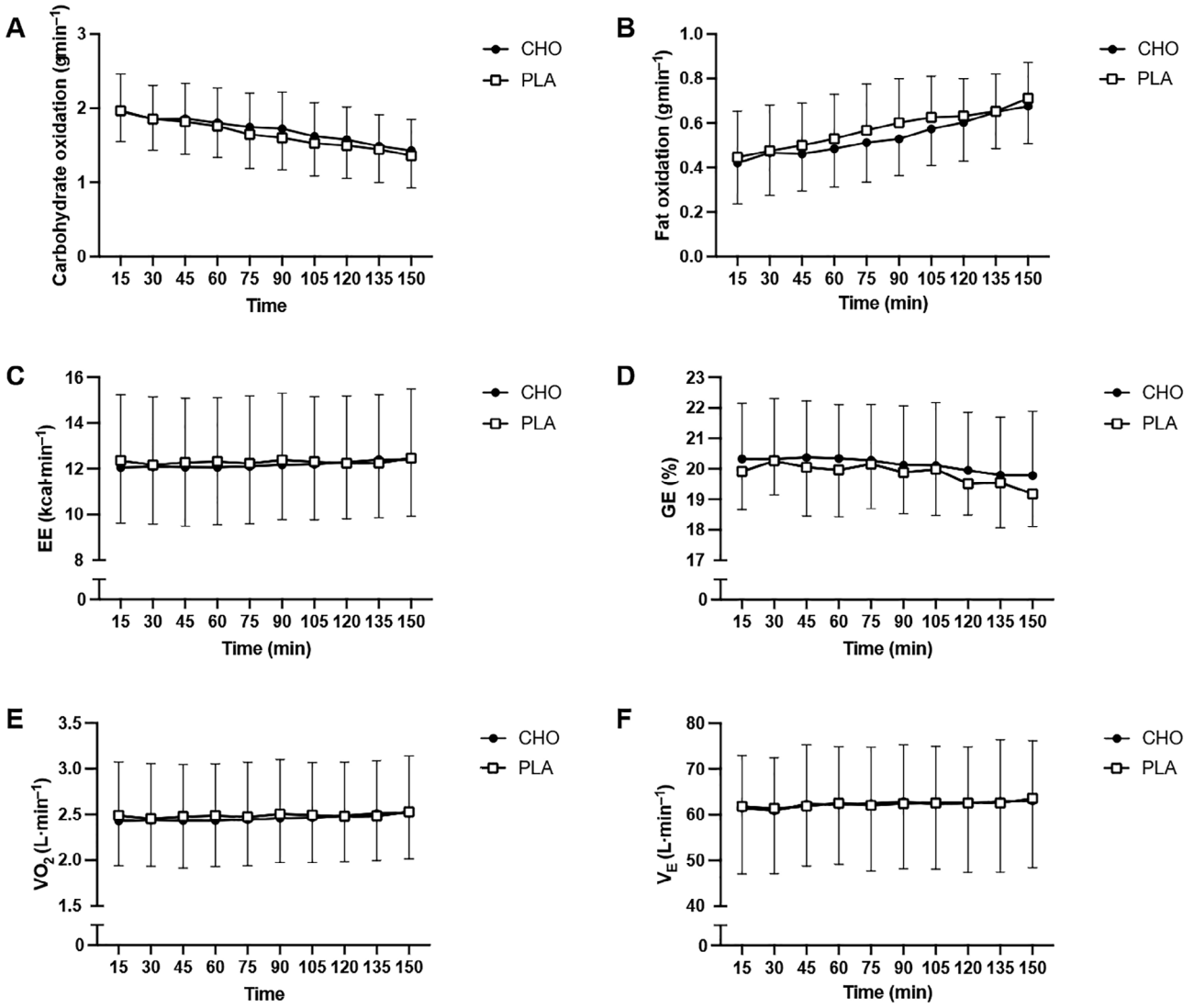

FIGURE 2 | (A) Carbohydrate oxidation rate, (B) fat oxidation rate, (C) energy expenditure (EE), (D) gross cycling efficiency (GE), (E) rate of oxygen consumption (VO2), and (F) minute ventilation (V_E) during the preload phase of CHO and PLA. Data are means with standard deviations.

PLA (5.8 ± 0.7 mmol·L^{-1} vs. 4.7 ± 0.3 mmol·L^{-1}, Δ 1.0 ± 0.7 [0.5, 1.5] mmol·L^{-1}, $p = 0.0008$) and higher in CHO than PLA (5.5 ± 0.5 mmol·L^{-1}, Δ 0.7 ± 0.5 [0.4, 1.1] mmol·L^{-1}, $p = 0.0008$). No significant difference was found between FRESH and CHO (Figure 3B). Power output at VT_1 was significantly greater in FRESH than PLA (193 ± 56 W vs. 176 ± 47 W, Δ 17 ± 15 [9, 26] W, $p = 0.003$) and in CHO than PLA (189 ± 55 W, Δ 13 ± 17 [2, 23] W, $p = 0.0466$). The difference was not significant between FRESH and CHO (Figure 4A). In PLA, the contribution to the reduction in power output at VT_1 was greater for metabolic power than for metabolic efficiency (−10 ± 18 W vs. −6 ± 18 W), whereas the opposite pattern was observed in CHO (−1 ± 16 W vs. −4 ± 10 W). The comparison between conditions for metabolic power and metabolic efficiency was not statistically significant ($p = 0.096$ vs. $p = 0.6534$, respectively; Figure 4C).

3.4 | Three-Minute All-Out Test

One participant did not complete the 3MAOT, hence the data presented here are from $n = 12$. Critical power was significantly greater in FRESH than PLA (312 ± 72 W vs. 298 ± 67 W; Δ 13.7 ± 17.5 W, 95% CI [0.1, 27.4], adjusted $p = 0.049$; Figure 5A). CP in CHO (304 ± 72 W) did not differ significantly from FRESH (Δ 7.7 ± 20.0 W, 95% CI [−7.9, 23.3], adjusted $p = 0.41$) or PLA (Δ 6.0 ± 26.0 W, 95% CI [−14.3, 26.3], adjusted $p = 0.71$). W′ was significantly higher in FRESH than CHO (10.9 ± 5.5 kJ vs. 8.6 ± 5.6 kJ; Δ 2.4 ± 1.8 kJ, 95% CI [1.0, 3.8], adjusted $p = 0.0018$), whereas FRESH vs. PLA (8.2 ± 3.7 kJ; Δ 2.7 ± 3.9 kJ, 95% CI [−0.3, 5.7], adjusted $p = 0.081$) and CHO vs. PLA (Δ 0.3 ± 4.2 kJ, 95% CI [−3.0, 3.6], adjusted $p = 0.97$) were not significant (Figure 5C). Because all CHO–PLA differences were non-significant with wide confidence intervals, these results do not establish equivalence between CHO and PLA, nor a protective effect of CHO.

4 | Discussion

The aim of the present study was to investigate if carbohydrate ingestion at 15 g·h^{-1} during prolonged moderate-intensity cycling impacts durability of the moderate-to-heavy and heavy-to-severe intensity transitions. We hypothesized that carbohydrate

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

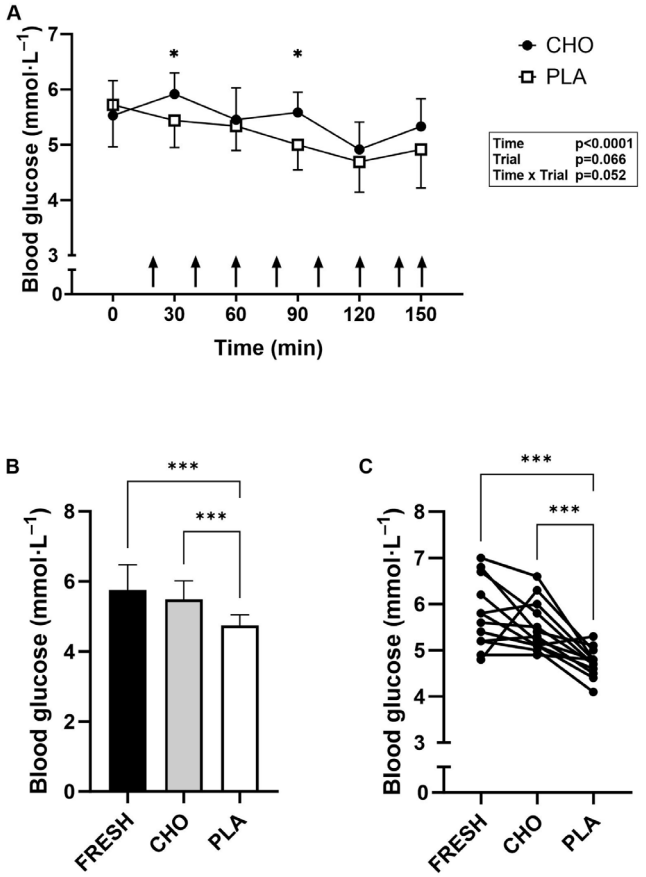

FIGURE 3 | (A) Blood glucose concentration during the 150-min preload phase in CHO and PLA. Arrows indicate the timing of carbohydrate or placebo ingestion (arrow length does not reflect volume; the last drink was half the volume of the others). * indicates a significant timepoint difference between CHO and PLA in exploratory post hoc comparisons, in the absence of a significant overall condition × time interaction. (B) Mean blood glucose concentration immediately before the five-step incremental test. (C) Individual blood glucose concentration immediately before the five-step incremental test. Data are means with standard deviations (A and B) or individual values (C). $^{*}p \leq 0.05$, $^{**}p \leq 0.01$, $^{***}p \leq 0.001$ between-trials.

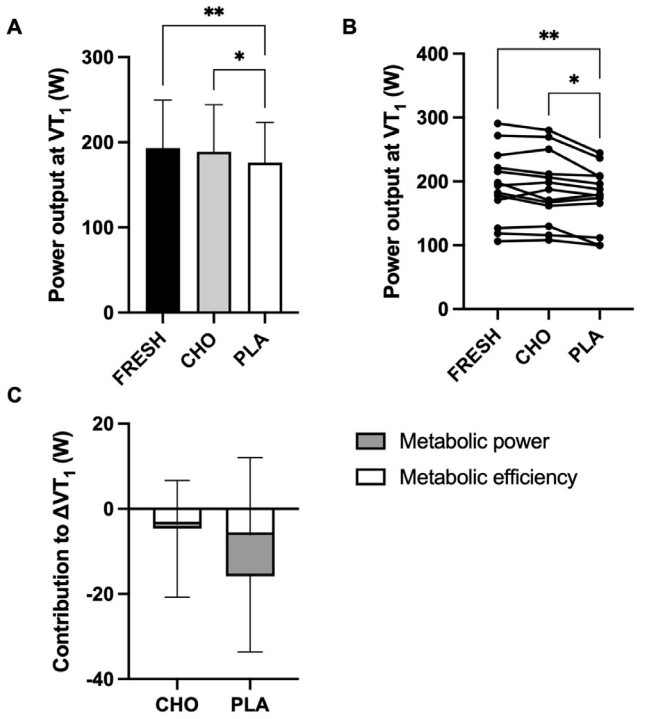

FIGURE 4 | (A) Mean power output at first ventilatory threshold in the FRESH, CHO and PLA trials, (B) Individual power output at first ventilatory threshold in the FRESH, CHO and PLA trials, (C) Contribution to changes in the power output at the first ventilatory threshold (VT_1) by losses in metabolic efficiency and metabolic energy expenditure at the threshold after a period of prolonged exercise in the CHO and PLA trials. Data are means with standard deviations (A and C) or individual values (B). $^{*}p \leq 0.05$, $^{**}p \leq 0.01$.

ingestion at 15 g·h^{-1} would be sufficient to maintain blood glucose concentration and attenuate the decline in power output at the intensity domain transitions typically observed following prolonged exercise. The primary findings were that 15 g·h^{-1} of carbohydrate ingestion during prolonged moderate-intensity cycling: (i) attenuated the power output decline at the moderate-to-heavy intensity transition and (ii) increased blood glucose concentrations immediately following 150 min of cycling, with transient elevations observed during the preload phase. These results suggest that carbohydrate ingestion at rates below commonly recommended intakes (~30–90 g·h^{-1}, depending on exercise duration and carbohydrate source) is sufficient to improve durability of the moderate-to-heavy transition during prolonged moderate-intensity cycling. These data have implications for training stress management and our understanding of the mechanisms behind durability.

As expected, prolonged cycling reduced power output at the moderate-to-heavy and heavy-to-severe intensity transitions by ~9% and ~4%, respectively, in the PLA vs. FRESH trial (Figures 4A and 5A). Consistent with our hypothesis, 15 g·h^{-1} of carbohydrate ingestion during prolonged cycling successfully mitigated the reduction in power output at the moderate-to-heavy transition (Figure 4A). These findings are consistent with previous studies reporting carbohydrate ingestion at ~60 g·h^{-1} during prolonged exercise that attenuates the reduction in power output at the intensity domain transitions [12, 13], and align with another study reporting increased exercise capacity with carbohydrate ingestion at ~10 g·h^{-1} [30]. Our data are the first to demonstrate that durability of the moderate-to-heavy intensity transition can be improved with 15 g·h^{-1} of carbohydrate ingestion during prolonged exercise. These data have practical significance for those monitoring training stress using the intensity domains model and for our understanding of the mechanisms behind durability. However, in contrast to our hypothesis, 15 g·h^{-1} of carbohydrate ingestion during prolonged cycling did not improve power output at the heavy-to-severe transition in CHO vs. PLA, although power output was only reduced vs. FRESH in PLA (Figure 5A). This uncertainty may be a result of the relatively modest ~4% reduction in power output at the heavy-to-severe transition in PLA vs. FRESH (~4%). Therefore, our data do not clearly demonstrate that 15 g·h^{-1} of carbohydrate ingestion during prolonged cycling is sufficient to improve durability of the heavy-to-severe transition, and future studies of this effect may require larger sample sizes and/or more demanding prolonged exercise protocols. Similarly, Fleitas-Paniagua et al. [36] found that carbohydrate effects on

16000838, 2026, 1, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

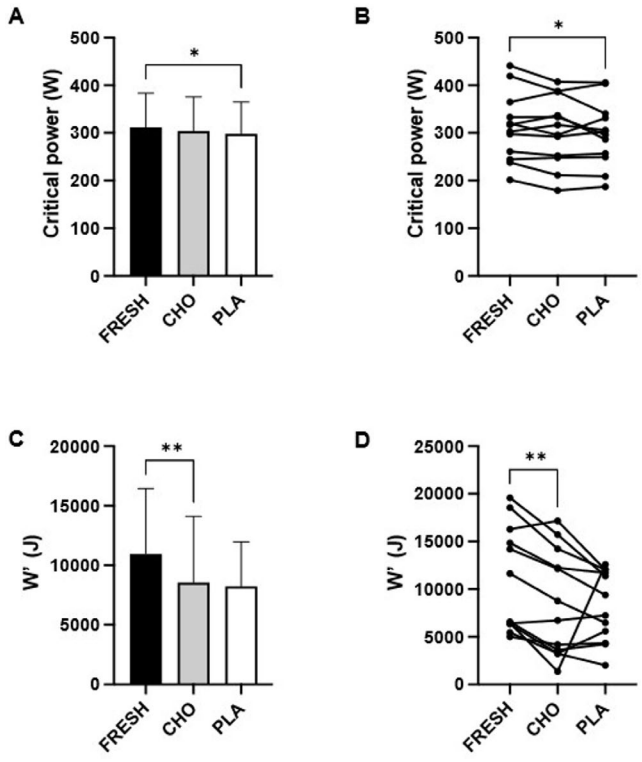

FIGURE 5 | (A) Mean critical power, (B) Individual critical power, (C) Mean W′, (D) Individual W′ in the FRESH, CHO and PLA trials. Data are means and standard deviations (A and C) and individual values (B and D). *$p \leq 0.05$, **$p \leq 0.01$.

subsequent time-trial performance depended on the preceding exercise intensity, with no benefit after moderate-intensity cycling. Because the 3MAOT followed both the prolonged preload and the incremental test, the CP and W′ values reported here cannot be attributed to the preload alone, but to its combined effect with the incremental exercise.

The low rate of carbohydrate ingestion in CHO appeared to transiently spike blood glucose concentrations after 30 and 90 min (Figure 3A) of the 150-min prolonged cycling, likely reflecting the timing of carbohydrate ingestion with respect to blood sampling. Specifically, transient increases in blood glucose appeared when measurements were taken 10 min after carbohydrate ingestion, whereas this effect was not evident when sampling occurred 20 min post-ingestion. These spikes resulted in a greater, but not statistically significant, blood glucose area under the curve in CHO than PLA (819 ± 46 mmol·min·L^{-1} vs. 774 ± 60 mmol·min·L^{-1}, $p = 0.053$; respectively). Although interesting, these exploratory observations do not provide evidence of sustained maintenance of blood glucose. In contrast to studies employing higher carbohydrate ingestion rates (≥ 60 g·h^{-1}), no significant differences in blood glucose concentrations were observed between CHO and PLA during the final stages of the prolonged exercise bout [13, 37]. However, the blood glucose concentration was significantly higher at the sampling point immediately prior to the five-step incremental test in CHO vs. PLA (Figure 3B), likely due to the final bolus of carbohydrate ingestion, which occurred ~10 min prior to this sampling timepoint. Collectively, our data raise the possibility that 15 g·h^{-1} of carbohydrate ingestion may partially mitigate the reduction in blood glucose concentration during prolonged moderate-intensity cycling and is consistent with a role of ingestion frequency on the stability and maintenance of blood glucose concentration during prolonged exercise. Therefore, future studies should investigate whether modifying the timing of carbohydrate ingestion, while maintaining the same overall ingestion rate, results in different glycaemic profiles. These studies should include more frequent blood sampling timepoints and/or continuous interstitial measures to gain a comprehensive picture of the glycaemic response.

Accordingly, our data provide some support for our hypothesis that improved durability of the moderate-to-heavy transition with carbohydrate ingestion during prolonged exercise may be at least partially attributable to effects on blood glucose concentrations. Although blood glucose concentrations did not fall below the threshold for hypoglycaemia (< 3.0 mmol·L^{-1}) [38], blood glucose concentrations were higher immediately prior to the incremental test in CHO than PLA (Figure 3B,C). It is therefore possible that modest reductions in blood glucose concentrations, within physiological ranges, negatively affect durability. In support, Elghobashy et al. [24] demonstrated that elevated interstitial glucose was associated with improved exercise capacity, even though hypoglycaemia did not occur in the control condition. Therefore, altering glycaemia, rather than simply preventing hypoglycaemia, may be an important determinant of durability.

It is possible that the low rate of carbohydrate ingestion in CHO improved durability via activation of oral sensory receptors. Several studies have demonstrated that the presence of carbohydrates in the oral cavity, without ingestion, enhances neuromuscular function [39, 40]. More specifically, carbohydrate mouth rinsing, compared to artificially-sweetened solutions, has been shown to improve time trial performance [41] and to activate brain regions associated with reward and motor control, including the anterior cingulate cortex, striatum, insula/frontal operculum, and orbitofrontal cortex [41]. Therefore, the stimulation of oral carbohydrate receptors in CHO may have contributed to improved durability through enhanced neuromuscular function, including greater motor unit recruitment, more effective fiber-type activation, and/or improved motor unit synchronization. The hypothesis that carbohydrate mouth rinsing enhances neuromuscular function, possibly contributing to improved durability, is supported by evidence showing greater electromyographic amplitude during moderate-intensity cycling compared to placebo conditions [42]. Therefore, future research should investigate the effects of low-dose carbohydrate ingestion and carbohydrate mouth rinsing, compared to placebo, on durability, with measures of neuromuscular function.

An additional mechanism that could contribute to the improved durability observed with low-dose carbohydrate ingestion is greater availability of exogenous glucose for oxidation, resulting in a reduced rate of net skeletal muscle glycogen utilization to support energy expenditure [26]. Plausibly, a reduced rate of net muscle glycogen utilization during exercise could improve durability via preservation of muscle contractile function, as muscle glycogen depletion impairs calcium handling [43]. However, many studies with much higher rates of carbohydrate ingestion during exercise have not observed reduced net muscle glycogen utilization [22, 26, 37], and a recent meta-analysis indicates that any effect of carbohydrate ingestion on net muscle glycogen utilization is modest, even

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

at higher ingestion rates [20]. Therefore, we feel it is unlikely that the improved durability in CHO is attributable to effects on skeletal muscle glycogen availability, but, as we did not measure muscle glycogen use, we cannot definitively rule this out. Thus, to understand the mechanisms through which low-dose carbohydrate ingestion during prolonged exercise improves durability of the moderate-to-heavy transition, future studies should include measurements of blood glucose concentrations alongside net skeletal muscle glycogen utilization and endogenous carbohydrate oxidation rates, with assessments of neuromuscular function. To ascertain whether carbohydrate ingestion during prolonged exercise improves durability specifically via its effects on blood glucose concentration, future studies could employ controlled glucose infusion protocols, such as euglycaemic clamps, to maintain blood glucose at fixed levels during exercise, thereby enabling a direct assessment of durability alongside relevant neuromuscular and physiological measures described above.

Our data align with previous studies reporting that the reduction in power output at the moderate-to-heavy intensity transition following prolonged cycling is primarily driven by reductions in metabolic power rather than metabolic efficiency [8, 13]. In PLA, metabolic power and metabolic efficiency accounted for ~61% and ~39% of the loss of power output at the moderate-to-heavy intensity transition, respectively (Figure 4C). Whilst the comparison between CHO and PLA was not significant, the effect of prolonged cycling on metabolic power in PLA was not seen in CHO (Figure 4C). This effect was observed with 60 $g \cdot h^{-1}$ of carbohydrate ingestion previously [13]. Speculatively, the improved maintenance of metabolic power in CHO could be related to improved neural drive, given carbohydrate mouth rinsing activates brain regions involved in motor control [41]. Accordingly, future research should further investigate neuromuscular responses to prolonged cycling under different carbohydrate feeding strategies, while also comparing these approaches with carbohydrate mouth rinsing. Collectively, the literature suggests that the reduction in power output at the moderate-to-heavy intensity transition during prolonged cycling is primarily driven by reduced metabolic power, whereas a protective effect of carbohydrate ingestion remains to be established.

Low-dose carbohydrate ingestion did not translate into a preservation of work above critical power (W′) in CHO. This is in line with previous studies featuring carbohydrate ingestion at higher rates [12]. Our ability to interpret these data is limited by the absence of blood glucose data following the five-step incremental test and immediately prior to the 3MAOT. The five-step incremental test included exercise intensities within the heavy domain, which may elevate blood glucose concentrations even in the PLA condition [44], potentially masking differences between conditions and therefore not allowing us to exclude the possibility that blood glucose contributes to the preservation of W′. Speculatively, the reduction in W′ following prolonged exercise is driven by effects of muscle glycogen depletion on calcium handling. Specifically, reduced muscle glycogen availability may impair the ability of the sarcoplasmic reticulum to release calcium [43], and therefore muscle contractile function [45] and force-generating capacity [46, 47]. This aligns with the absence of an effect of carbohydrate ingestion on durability of W′, given the effect of carbohydrate ingestion on muscle glycogen utilization is modest during moderate-intensity exercise [20].

Taken together, these findings suggest low rates of carbohydrate ingestion during prolonged cycling improve durability of the moderate-to-heavy transition, possibly via alteration of blood glucose concentrations. Effects on the heavy-to-severe transition were unclear and, given the smaller effect of our prolonged exercise protocol on power output at the heavy-to-severe vs. moderate-to-heavy transition, future examinations may require a larger sample size and/or more demanding prolonged exercise protocol. Future research should directly compare different carbohydrate ingestion rates, including low (i.e., 5–20 $g \cdot h^{-1}$) and high-dose strategies (i.e., 90–120 $g \cdot h^{-1}$), as well as carbohydrate mouth rinsing. These studies should include hormonal (e.g., insulin, glucagon, cortisol, and catecholamines) and neuromuscular responses (e.g., maximum voluntary torque, electromyographic amplitude and median power frequency) to provide further insight into the physiological processes involved. From a practical standpoint, whilst our findings suggest that low-dose carbohydrate ingestion may be sufficient to enhance durability when ingested during moderate-intensity cycling, these results should be interpreted with caution, as the experimental protocol does not fully replicate the physiological and mechanical demands associated with stochastic prolonged cycling, which more closely reflects real-world training and competitive conditions. Severe-intensity exercise increases carbohydrate oxidation and blood glucose concentrations [48], likely due to increased catecholamine concentrations [49]. Therefore, future investigations of the effects of low-dose carbohydrate ingestion on durability could employ protocols that more closely simulate training and racing conditions, such as the inclusion of a preload phase incorporating high-intensity efforts in the heavy and severe-intensity domains. These data would determine if the results observed here are generalizable to a range of training and competition intensity profiles.

In conclusion, carbohydrate ingestion at a rate of 15 $g \cdot h^{-1}$ during prolonged moderate-intensity cycling attenuates the decline in power output at the moderate-to-heavy transition. Carbohydrate ingestion at this rate may have also induced transient increases in blood glucose concentrations, including immediately prior to the assessment of the moderate-to-heavy transition. These findings suggest that improved durability of the moderate-to-heavy intensity transition during prolonged, moderate-intensity cycling can be achieved with carbohydrate ingestion at low rates. These data do not imply that sports nutrition guidelines to maximize endurance performance should be revised.

4.1 | Perspective

Durability is increasingly regarded as having important implications in endurance training stress management. Prior carbohydrate feeding studies have demonstrated improvements in durability with ingestion rates $\geq$60 $g \cdot h^{-1}$. If our data showing that lower carbohydrate ingestion rates improve durability of the moderate-to-heavy transition are confirmed, this may inform training programming and load monitoring. Future work should compare low ($\leq$15 $g \cdot h^{-1}$) and high (90–120 $g \cdot h^{-1}$) carbohydrate ingestion rates on durability directly and compare these effects with mouth-rinsing trials to separate metabolic from

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

oral-sensory effects. Ideally, these studies will include denser blood sampling or continuous glucose monitoring and measurement of muscle and liver glycogen and neuromuscular function. Larger samples, biological sex comparisons, and more demanding, stochastic prolonged exercise protocols featuring heavy- and severe-intensity bouts are needed to examine durability of the heavy-to-severe intensity transition and improve ecological validity.

Acknowledgments

Open access publishing facilitated by Auckland University of Technology, as part of the Wiley - Auckland University of Technology agreement via the Council of Australasian University Librarians.

Funding

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. M. I. Black, A. M. Jones, J. R. Blackwell, et al., "Muscle Metabolic and Neuromuscular Determinants of Fatigue During Cycling in Different Exercise Intensity Domains," *Journal of Applied Physiology* 122, no. 3 (2017): 446–459, https://doi.org/10.1152/japplphysiol.00942.2016.

2. M. Burnley and A. M. Jones, "Power–Duration Relationship: Physiology, Fatigue, and the Limits of Human Performance," *European Journal of Sport Science* 18, no. 1 (2018): 1–12, https://doi.org/10.1080/17461391.2016.1249524.

3. B. Hunter, E. Maunder, A. M. Jones, G. Gallo, and D. Muniz-Pumares, "Durability as an Index of Endurance Exercise Performance: Methodological Considerations," *Experimental Physiology* 110, no. 11 (2025): 1612–1624, https://doi.org/10.1113/EP092120.

4. E. Maunder, S. Seiler, M. J. Mildenhall, A. E. Kilding, and D. J. Plews, "The Importance of 'Durability' in the Physiological Profiling of Endurance Athletes," *Sports Medicine* 51, no. 8 (2021): 1619–1628, https://doi.org/10.1007/s40279-021-01459-0.

5. K. S. Seiler and G. Ø. Kjerland, "Quantifying Training Intensity Distribution in Elite Endurance Athletes: Is There Evidence for an "Optimal" Distribution?," *Scandinavian Journal of Medicine and Science in Sports* 16, no. 1 (2006): 49–56, https://doi.org/10.1111/j.1600-0838.2004.00418.x.

6. G. Gallo, E. L. Faelli, P. Ruggeri, et al., "Power Output at the Moderate-To-Heavy Intensity Transition Decreases in a Non-Linear Fashion During Prolonged Exercise," *European Journal of Applied Physiology* 124, no. 8 (2024): 2353–2364, https://doi.org/10.1007/s00421-024-05440-3.

7. K. Hamilton, A. E. Kilding, D. J. Plews, et al., "Durability of the Moderate-To-Heavy-Intensity Transition Is Related to the Effects of Prolonged Exercise on Severe-Intensity Performance," *European Journal of Applied Physiology* 124, no. 8 (2024): 2427–2438, https://doi.org/10.1007/s00421-024-05459-6.

8. J. D. Stevenson, A. E. Kilding, D. J. Plews, and E. Maunder, "Prolonged Cycling Reduces Power Output at the Moderate-To-Heavy Intensity Transition," *European Journal of Applied Physiology* 122, no. 12 (2022): 2673–2682, https://doi.org/10.1007/s00421-022-05036-9.

9. J. D. Stevenson, A. E. Kilding, D. J. Plews, and E. Maunder, "Prolonged Exercise Shifts Ventilatory Parameters at the Moderate-To-Heavy Intensity Transition," *European Journal of Applied Physiology* 124, no. 1 (2024): 309–315, https://doi.org/10.1007/s00421-023-05285-2.

10. I. E. Clark, A. Vanhatalo, S. J. Bailey, et al., "Effects of Two Hours of Heavy-Intensity Exercise on the Power–Duration Relationship," *Medicine & Science in Sports & Exercise* 50, no. 8 (2018): 1658–1668, https://doi.org/10.1249/MSS.0000000000001601.

11. I. E. Clark, A. Vanhatalo, C. Thompson, et al., "Changes in the Power-Duration Relationship Following Prolonged Exercise: Estimation Using Conventional and All-Out Protocols and Relationship With Muscle Glycogen," *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* 317, no. 1 (2019): R59–R67, https://doi.org/10.1152/ajpregu.00031.2019.

12. I. E. Clark, A. Vanhatalo, C. Thompson, et al., "Dynamics of the Power-Duration Relationship During Prolonged Endurance Exercise and Influence of Carbohydrate Ingestion," *Journal of Applied Physiology* 127, no. 3 (2019): 726–736, https://doi.org/10.1152/japplphysiol.00207.2019.

13. H. Dudley-Rode, C. Zinn, D. J. Plews, T. Charoensap, and E. Maunder, "Carbohydrate Ingestion During Prolonged Exercise Blunts the Reduction in Power Output at the Moderate-To-Heavy Intensity Transition," *European Journal of Applied Physiology* 125, no. 5 (2025): 1349–1359, https://doi.org/10.1007/s00421-024-05687-w.

14. B. R. Norte, M. M. Slinn, K. O. Johnson, et al., "Graded Carbohydrate Ingestion up to 120 $g{\cdot}h^{-1}$ Attenuates the Reduction in Critical Power Following 3 h of Moderate-Intensity Exercise in a Dose-Dependent Manner," *Scandinavian Journal of Medicine and Science in Sports* 36, no. 6 (2026): e70326, https://doi.org/10.1111/sms.70326.

15. E. F. Coyle, J. M. Hagberg, B. F. Hurley, W. H. Martin, A. A. Ehsani, and J. O. Holloszy, "Carbohydrate Feeding During Prolonged Strenuous Exercise Can Delay Fatigue," *Journal of Applied Physiology* 55, no. 1 (1983): 230–235, https://doi.org/10.1152/jappl.1983.55.1.230.

16. A. E. Jeukendrup, "Carbohydrate and Exercise Performance: The Role of Multiple Transportable Carbohydrates," *Current Opinion in Clinical Nutrition and Metabolic Care* 13, no. 4 (2010): 452–457, https://doi.org/10.1097/MCO.0b013e328339de9f.

17. T. Podlogar, Š. Bokal, S. Cirnski, and G. A. Wallis, "Increased Exogenous but Unaltered Endogenous Carbohydrate Oxidation With Combined Fructose-Maltodextrin Ingested at 120 g h^{-1} Versus 90 g h^{-1} at Different Ratios," *European Journal of Applied Physiology* 122, no. 11 (2022): 2393–2401, https://doi.org/10.1007/s00421-022-05019-w.

18. R. L. P. G. Jentjens, J. Achten, and A. E. Jeukendrup, "High Oxidation Rates From Combined Carbohydrates Ingested During Exercise," *Medicine & Science in Sports & Exercise* 36, no. 9 (2004): 1551–1558, https://doi.org/10.1249/01.MSS.0000139796.07843.1D.

19. J. T. Gonzalez, C. J. Fuchs, F. E. Smith, et al., "Ingestion of Glucose or Sucrose Prevents Liver but Not Muscle Glycogen Depletion During Prolonged Endurance-Type Exercise in Trained Cyclists," *American Journal of Physiology. Endocrinology and Metabolism* 309, no. 12 (2015): E1032–E1039, https://doi.org/10.1152/ajpendo.00376.2015.

20. J. A. Rothschild, H. Dudley-Rode, H. Carpenter, A. S. M. Smith, D. J. Plews, and E. Maunder, "Carbohydrate Ingestion During Prolonged Exercise and Net Skeletal Muscle Glycogen Utilization: A Meta-Analysis," *Journal of Applied Physiology* 140, no. 1 (2026): 76–87, https://doi.org/10.1152/japplphysiol.00861.2025.

21. J. Bergström and E. Hultman, "A Study of the Glycogen Metabolism During Exercise in Man," *Scandinavian Journal of Clinical and Laboratory Investigation* 19, no. 3 (1967): 218–228, https://doi.org/10.3109/00365516709090629.

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

22. M. Hargreaves, D. L. Costill, A. Coggan, W. J. Fink, and I. Nishibata, "Effect of Carbohydrate Feedings on Muscle Glycogen Utilization and Exercise Performance," *Medicine & Science in Sports & Exercise* 16, no. 3 (1984): 219–222, https://doi.org/10.1249/00005768-198406000-00004.

23. D. T. Thomas, K. A. Erdman, and L. M. Burke, "Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and Athletic Performance," *Journal of the Academy of Nutrition and Dietetics* 116, no. 3 (2016): 501–528, https://doi.org/10.1016/j.jand.2015.12.006.

24. M. E. Elghobashy, A. J. Richards, R. Malekzadeh, et al., "Carbohydrate Ingestion Increases Interstitial Glucose and Mitigates Neuromuscular Fatigue During Single-Leg Knee Extensions," *Medicine & Science in Sports & Exercise* 56, no. 8 (2024): 1495–1504, https://doi.org/10.1249/MSS.0000000000003440.

25. L. Nybo, "CNS Fatigue and Prolonged Exercise: Effect of Glucose Supplementation," *Medicine & Science in Sports & Exercise* 35, no. 4 (2003): 589–594, https://doi.org/10.1249/01.MSS.0000058433.85789.66.

26. E. F. Coyle, A. R. Coggan, M. K. Hemmert, and J. L. Ivy, "Muscle Glycogen Utilization During Prolonged Strenuous Exercise When Fed Carbohydrate," *Journal of Applied Physiology* 61, no. 1 (1986): 165–172, https://doi.org/10.1152/jappl.1986.61.1.165.

27. G. A. Brooks, "The Precious Few Grams of Glucose During Exercise," *International Journal of Molecular Sciences* 21, no. 16 (2020): 5733, https://doi.org/10.3390/ijms21165733.

28. T. D. Noakes, P. J. Prins, A. Buga, D. P. D'Agostino, J. S. Volek, and A. P. Koutnik, "Carbohydrate Ingestion on Exercise Metabolism and Physical Performance," *Endocrine Reviews* 47, no. 2 (2026): 191–243, https://doi.org/10.1210/endrev/bnaf038.

29. R. Murray, G. L. Paul, J. G. Seifert, and D. E. Eddy, "Responses to Varying Rates of Carbohydrate Ingestion During Exercise," *Medicine & Science in Sports & Exercise* 23, no. 6 (1991): 713–718, https://doi.org/10.1249/00005768-199106000-00010.

30. P. J. Prins, T. D. Noakes, A. Buga, et al., "Carbohydrate Ingestion Eliminates Hypoglycemia and Improves Endurance Exercise Performance in Triathletes Adapted to Very Low- and High-Carbohydrate Isocaloric Diets," *American Journal of Physiology-Cell Physiology* 328, no. 2 (2025): C710–C727, https://doi.org/10.1152/ajpcell.00583.2024.

31. J. J. James, O. K. Leach, A. M. Young, et al., "The Exercise Power-Duration Relationship Is Equally Reproducible in Eumenorrheic Female and Male Humans," *Journal of Applied Physiology* 134, no. 2 (2023): 230–241, https://doi.org/10.1152/japplphysiol.00416.2022.

32. A. Vanhatalo, J. H. Doust, and M. Burnley, "Determination of Critical Power Using a 3-Min All-Out Cycling Test," *Medicine & Science in Sports & Exercise* 39, no. 3 (2007): 548–555, https://doi.org/10.1249/mss.0b013e31802dd3e6.

33. A. E. Jeukendrup and G. A. Wallis, "Measurement of Substrate Oxidation During Exercise by Means of Gas Exchange Measurements," *International Journal of Sports Medicine* 26 (2005): S28–S37, https://doi.org/10.1055/s-2004-830512.

34. M. Burnley, J. H. Doust, and A. Vanhatalo, "A 3-Min All-Out Test to Determine Peak Oxygen Uptake and the Maximal Steady State," *Medicine & Science in Sports & Exercise* 38, no. 11 (2006): 1995–2003, https://doi.org/10.1249/01.mss.0000232024.06114.a6.

35. E. Main, S. Yoon, S. L. James, et al., "Low Carbohydrate Availability Reduces Power Output at the Moderate-To-Heavy Transition, Impairs Efficiency, and Increases Median Power Frequency During Cycling in Females," *European Journal of Applied Physiology* 126, no. 9 (2026): 4875–4887, https://doi.org/10.1007/s00421-026-06260-3.

36. P. R. Fleitas-Paniagua, L. Rasica, R. D. A. Azevedo, et al., "Recommended but Not High Carbohydrate Dose Improves Performance After Heavy-But Not Moderate-Intensity Exercise in Recreationally Trained Participants," *Scandinavian Journal of Medicine & Science in Sports* 36, no. 5 (2026): e70288, https://doi.org/10.1111/sms.70288.

37. M. Hargreaves and C. A. Briggs, "Effect of Carbohydrate Ingestion on Exercise Metabolism," *Journal of Applied Physiology* 65, no. 4 (1988): 1553–1555, https://doi.org/10.1152/jappl.1988.65.4.1553.

38. International Hypoglycaemia Study Group, "Glucose Concentrations of Less Than 3.0 Mmol/L (54 mg/dL) Should be Reported in Clinical Trials: A Joint Position Statement of the American Diabetes Association and the European Association for the Study of Diabetes," *Diabetes Care* 40, no. 1 (2017): 155–157, https://doi.org/10.2337/dc16-2215.

39. I. Bazzucchi, F. Patrizio, F. Felici, A. Nicolò, and M. Sacchetti, "Carbohydrate Mouth Rinsing: Improved Neuromuscular Performance During Isokinetic Fatiguing Exercise," *International Journal of Sports Physiology and Performance* 12, no. 8 (2017): 1031–1038, https://doi.org/10.1123/ijspp.2016-0583.

40. R. Jeffers, R. Shave, E. Ross, E. J. Stevenson, and S. Goodall, "The Effect of a Carbohydrate Mouth-Rinse on Neuromuscular Fatigue Following Cycling Exercise," *Applied Physiology, Nutrition and Metabolism* 40, no. 6 (2015): 557–564, https://doi.org/10.1139/apnm-2014-0393.

41. E. S. Chambers, M. W. Bridge, and D. A. Jones, "Carbohydrate Sensing in the Human Mouth: Effects on Exercise Performance and Brain Activity," *Journal of Physiology* 587, no. 8 (2009): 1779–1794, https://doi.org/10.1113/jphysiol.2008.164285.

42. V. Bastos-Silva, A. Melo, A. Lima-Silva, F. Moura, R. Bertuzzi, and G. De Araujo, "Carbohydrate Mouth Rinse Maintains Muscle Electromyographic Activity and Increases Time to Exhaustion During Moderate but Not High-Intensity Cycling Exercise," *Nutrients* 8, no. 3 (2016): 49, https://doi.org/10.3390/nu8030049.

43. N. Ørtenblad, J. Nielsen, B. Saltin, and H. Holmberg, "Role of Glycogen Availability in Sarcoplasmic Reticulum Ca^{2+} Kinetics in Human Skeletal Muscle," *Journal of Physiology* 589, no. 3 (2011): 711–725, https://doi.org/10.1113/jphysiol.2010.195982.

44. J. Wahren, P. Felig, G. Ahlborg, and L. Jorfeldt, "Glucose Metabolism During Leg Exercise in Man," *Journal of Clinical Investigation* 50, no. 12 (1971): 2715–2725, https://doi.org/10.1172/JCI106772.

45. N. Ørtenblad, H. Westerblad, and J. Nielsen, "Muscle Glycogen Stores and Fatigue," *Journal of Physiology* 591, no. 18 (2013): 4405–4413, https://doi.org/10.1113/jphysiol.2013.251629.

46. D. G. Allen, H. Westerblad, J. A. Lee, and J. Lännergren, "Role of Excitation-Contraction Coupling in Muscle Fatigue," *Sports Medicine* 13, no. 2 (1992): 116–126, https://doi.org/10.2165/00007256-199213020-00007.

47. G. Sjøgaard, R. P. Adams, and B. Saltin, "Water and Ion Shifts in Skeletal Muscle of Humans With Intense Dynamic Knee Extension," *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* 248, no. 2 (1985): R190–R196, https://doi.org/10.1152/ajpregu.1985.248.2.R190.

48. J. M. Peake, S. J. Tan, J. F. Markworth, J. A. Broadbent, T. L. Skinner, and D. Cameron-Smith, "Metabolic and Hormonal Responses to Isoenergetic High-Intensity Interval Exercise and Continuous Moderate-Intensity Exercise," *American Journal of Physiology. Endocrinology and Metabolism* 307, no. 7 (2014): E539–E552, https://doi.org/10.1152/ajpendo.00276.2014.

49. M. J. Watt, K. F. Howlett, M. A. Febbraio, L. L. Spriet, and M. Hargreaves, "Adrenaline Increases Skeletal Muscle Glycogenolysis, Pyruvate Dehydrogenase Activation and Carbohydrate Oxidation During Moderate Exercise in Humans," *Journal of Physiology* 534, no. 1 (2001): 269–278, https://doi.org/10.1111/j.1469-7793.2001.t01-1-00269.x.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** sms70407-sup-0001-DataS1.xlsx.

16000838, 2026, 11, Downloaded from https://onlinelibrary.wiley.com/doi/10.1111/sms.70407 by Auckland University Of Technol, Wiley Online Library on [23/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License