STRUCTURAL AND MECHANISTIC DETERMINANTS OF ENDURANCE PERFORMANCE

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STRUCTURAL AND MECHANISTIC DETERMINANTS OF ENDURANCE PERFORMANCE

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Table of Contents

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Editorial: Structural and mechanistic determinants of endurance performance

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Editorial on the Research Topic
Editorial: Structural and mechanistic determinants of endurance performance

Endurance performance is a multifactorial phenomenon. Physiologically, endurance performance depends on high maximal oxygen uptake, anaerobic thresholds, and movement economy. The precise mechanisms mediating these factors with respect to metabolic/muscular efficiency (mitochondrial amount, muscle capillarization, and others) are still unclear. Regarding biomechanics, the high economy stems from executing ideal mechanical patterns that involve the application of forces with the appropriate magnitude, direction, and timing while avoiding non-productive movements as an uncoordinated gait to optimize the transmission efficiency (Peyré-Tartaruga and Coertjens, 2018). In addition, biomechanical factors, such as muscle size, muscle architecture and quality, and tendon mechanical properties, can also help to determine long-term sports endurance performance. Endurance sports performance can also be understood in terms of muscle recruitment (e.g., muscle activation, or neuromuscular economy) during a specific motor task to be performed in that sport. Anthropometric factors, such as height, body mass, percentage of lean mass, and length of the upper or lower limbs, can also prove to be crucial for understanding which variables can significantly determine endurance sports performance.

Endurance determinants

The present manuscript reports interesting information on the complexity of the factors affecting endurance performance. Despite this complexity, most of the studies included in this editorial investigated the effects of physiological variables on endurance performance. Indeed, Figueiredo et al. demonstrated the value of peak running velocity and critical speed in determining 5-km running performance, suggesting that the well-structured and periodized training program should take these variables into consideration to improve the 5-km performance of recreational runners. Moreover, foot strike patterns seem to change across running speeds according to the foot strike index. Ekizos et al. observed a similar foot strike index with increased speeds in most runners (particularly in rearfoot strikers). However, some mid-forefoot strikers decrease the foot strike index with increasing speed. This could have implications for the metabolic energy consumption of mid-forefoot striker runners, typically measured at low speeds for the assessment of running economy. The higher foot strike index in the mid-forefoot striker runners results in distinct distributions of muscular output in the lower extremities compared with rearfoot strikers (i.e., higher moments at the ankle and lower moments at the knee joint for mid-forefoot striker runners). Additionally, Fong and Powell showed that greater breast support is associated with improved oxygen consumption (absolute and relative) and running economy in women runners. The breast support effect on oxygen consumption and running economy is influenced by breast size, with larger breasted athletes obtaining greater improvements in running performance than smaller breasted women. The use of face masks during the incremental running test affected physical and cognitive performance and maximal oxygen uptake in Slimani et al. study, suggesting the importance of avoiding cloth face mask use during maximal aerobic tests.

Otherwise, Alejo et al. reported that physiological endurance cycling indicators (e.g., maximum oxygen uptake, peak power output and respiratory compensation point) and 8-min time-trial performance are greater in professional and under-23 years cyclists than in junior cyclists. Furthermore, professional cyclists presented a higher ventilatory threshold compared with under-23 and junior cyclists. Some differences were also found in anthropometric parameters, with professional cyclists showing a lower relative fat mass and higher muscle mass than under-23 and junior cyclists. Similarly, no consistent differences were found between age categories for strength/power indicators. However, the results of Kominami et al. showed that the respiratory compensation point and ventilatory threshold are poor indicators of lactate buffering capacity without robust effects with age during exercise. Exercise tolerance decreases with age. Furthermore, mixed-reality sports can be potential approaches for endurance performance. Westmattelmann et al. investigated the influence of different power parameters, body mass and height on Virtual cycling Tour de France 2020 performance. The results showed that relative power output explains variance in performance. In addition, the authors explained that body mass and height can explain the results in only a few stages of the Virtual Tour de France, and lower body mass in particular determines race success in the mountain stages. Understanding human endurance performance is a complex task that increasingly demands from researchers, coaches and athletes knowledge of the multiple components involved in assessments and training programs. In this manner, endurance performance is likely to defy the types of easy explanations sought by scientific reductionism and remain an important puzzle for those interested in biomechanics and physiological integration, among other aspects to be explored in the future (Joyner and Coyle, 2008).

Contrary to the findings for endurance indicators, intermittent sports (e.g., taekwondo) involve high-intensity movements interspersed by periods of low intensity. Sant'Ana et al. observed that the internal load of the roundhouse kick corresponds to the anaerobic threshold in taekwondo athletes and can be considered in the training prescription. In taekwondo, when planning a training program, it is necessary to consider the specific demands of the sport and its intermittent characteristics. Finally, Borghi-Silva et al. found that unloading the respiratory musculature with proportionally assisted ventilation accelerates haemodynamic and muscle oxygenation recovery. These beneficial effects improve tolerance to repeated (interval) exercise in patients with heart failure with a reduced left ventricular ejection fraction.

Therefore, based on the studies submitted for this editorial, we integrated physiological performance determinants for metabolic implications, especially on cycling and running endurance sports. Based on the present editorial, key physiological determinants may serve as targets for training strategies in sports such as cycling and running to optimize endurance performance.

Looking to the future

Some physiological variables (e.g., maximum oxygen uptake, ventilatory threshold and movement economy) discussed in the present manuscript particularly influence the determinants of endurance performance. The present article presented some exciting new factors affecting endurance performance. Determinants of endurance sports performance have been established over the last few decades, particularly the effect of physiological factors. However, few studies have aimed to understand the determinants of sports performance with integrative use in the different areas proposed by this editorial. However, multicomponent characteristics can be directly related to cycling endurance performance by highlighting the importance of anthropometric characteristics and cycling training potential over classically held traditional variables in relation to the limits of human performance. Therefore, it is necessary to investigate multiple components in more ecological tests for the evaluation of endurance performance. Finally, other components (e.g., integrating anthropometry, biomechanics, and physiology) may present new evidence to determine endurance performance and should be investigated in ecological conditions (Batterson et al., 2020; Kordi et al., 2020; Bohm et al., 2021). Furthermore, we hope that the present Research Topic will stimulate more researchers to pursue answers regarding the determinants of endurance performance by integrating anthropometric, physiological and biomechanical analyses, aiming to provide more solid research knowledge and subsequent practical application.

Author contributions

This manuscript was written by all authors listed (FL, FD, LA, LP-T and JP). All authors have performed editorial reviewing tasks for this Research Topic.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
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Proportional Assist Ventilation Improves Leg Muscle Reoxygenation After Exercise in Heart Failure With Reduced Ejection Fraction

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Background: Respiratory muscle unloading through proportional assist ventilation (PAV) may enhance leg oxygen delivery, thereby speeding off-exercise oxygen uptake ($\dot{V}O_2$) kinetics in patients with heart failure with reduced left ventricular ejection fraction (HFrEF).

Methods: Ten male patients (HFrEF = 26 ± 9%, age 50 ± 13 years, and body mass index 25 ± 3 kg m^2) underwent two constant work rate tests at 80% peak of maximal cardiopulmonary exercise test to tolerance under PAV and sham ventilation. Post-exercise kinetics of $\dot{V}O_2$, vastus lateralis deoxyhemoglobin ([deoxy-Hb + Mb]) by near-infrared spectroscopy, and cardiac output (Q_T) by impedance cardiography were assessed.

Results: PAV prolonged exercise tolerance compared with sham (587 ± 390 s vs. 444 ± 296 s, respectively; $p = 0.01$). PAV significantly accelerated $\dot{V}O_2$ recovery ($\tau = 56 \pm 22$ s vs. 77 ± 42 s; $p < 0.05$), being associated with a faster decline in Δ[deoxy-Hb + Mb] and Q_T compared with sham ($\tau = 31 \pm 19$ s vs. 42 ± 22 s and 39 ± 22 s vs. 78 ± 46 s, $p < 0.05$). Faster off-exercise decrease in Q_T with PAV was related to longer exercise duration ($r = -0.76$; $p < 0.05$).

Conclusion: PAV accelerates the recovery of central hemodynamics and muscle oxygenation in HFrEF. These beneficial effects might prove useful to improve the tolerance to repeated exercise during cardiac rehabilitation.

Keywords: blood flow, heart failure, non-invasive ventilation, hemodynamics, exercise recovery

INTRODUCTION

The rate at which oxygen uptake ($\dot{V}O_2$) decreases after dynamic exercise has been used to assess disease severity and prognosis and, more recently, the effectiveness of interventions in patients with heart failure with reduced ejection fraction (HFrEF) (Guazzi et al., 2004; Dall'Ago et al., 2006; Compostella et al., 2014; Georgantas et al., 2014; Fortin et al., 2015; Bailey et al., 2018). Although oxygen (O_2) delivery is usually in excess of the decreasing O_2 demands during recovery from exercise in normal subjects, this might not be the case in HFrEF, a phenomenon that helps to explain why the evaluation of exercise recovery kinetics has gained popularity in the clinical arena (Kemps et al., 2009; Poole et al., 2012).

Exercise recovery kinetics have been shown to be more reproducible than those at the onset of exercise, and less influenced by oscillatory breathing or the confounding effects of a prolonged "cardiodynamic" phase I (Francis et al., 2002; Kemps et al., 2007). Moreover, activities of daily living are characterized by their short-term and repetitive nature, thereby suggesting that fast recovery from effort is important for the successful completion of any subsequent task (Hirai et al., 2019).

In this context, a previous study has shown that unloading the respiratory musculature with proportional assist ventilation (PAV) was associated with improved peripheral muscle oxygenation during constant-load exercise, as indicated by blunted changes in Δ deoxyhemoglobin ([deoxi-Hb + Mb]) determined by near-infrared spectroscopy (NIRS) and longer exercise tolerance in patients with HFrEF (Borghi-Silva et al., 2008a), chronic obstructive pulmonary disease (COPD) (Borghi-Silva et al., 2008b), and HFrEF-COPD coexistence (da Luz Goulart et al., 2020).

Interestingly, inspiratory muscle training associated with whole-body training also improved the cardiorespiratory responses to exercise, leading to a faster $\dot{V}O_2$ recovery in HFrEF (Dall'Ago et al., 2006). Based on the previous evidence indicating that post-exercise $\dot{V}O_2$ kinetics can be accelerated by interventions focused on improving O_2 delivery (Borghi-Silva et al., 2008a), this study hypothesized that, compared to sham ventilation, the rate of increase in muscle reoxygenation would be accelerated by PAV in HFrEF. Confirmation of this hypothesis indicates that the beneficial effects of respiratory muscle unloading on leg O_2 delivery are not limited to the onset of exercise (Borghi-Silva et al., 2008a), lending support to the notion that $\dot{V}O_2$ recovery kinetics are clinically useful to assess the efficacy of interventions in this patient population.

MATERIALS AND METHODS

Subjects and Design

The current study cohort included 10 non-smoking male patients who were recruited from the HFrEF outpatient clinic of the Institution (Miocardiopathy Ambulatory, Division of Cardiology). Patients with HFrEF satisfied the following inclusion criteria: (1) diagnosis of HFrEF documented for at least 4 years; (2) three-dimensional echodopplercardiography showing left ventricular ejection fraction (LVEF) <35%; (3) New York association functional class II and III; and (4) no hospitalizations in the previous 6 months. All patients were optimally treated according to the American Heart Association/American College of Cardiology treatment recommendations for stage "C" patients (i.e., reduced LVEF and current or previous symptoms of heart failure) (Hunt et al., 2005). All patients were judged to be clinically stable and compensated on medical therapy at the time of evaluation. In addition, patients were familiarized with stationary bicycle cardiopulmonary exercise tests prior to data collection.

Patients were excluded from study if they (1) demonstrate evidence of obstructive pulmonary disease [forced expiratory volume in 1 s (FEV_1)/forced vital capacity (FVC) ratio of <70%]; (2) have a history of smoking; (3) have a history of exercise-induced asthma; (4) have unstable angina or significant cardiac arrhythmias; (5) have anemia (hemoglobin <13 g%); (6) had myocardial infarction within the previous 12 months; (7) have primary valvular heart disease, neuromuscular or musculoskeletal disease, or other potential causes of dyspnea or fatigue; or (8) had participated in cardiovascular rehabilitation in the preceding year. Patients gave a written informed consent, and the study protocol was approved by the Institutional Medical Ethics Committee (CEP 0844/06).

Study Protocol

Subjects performed a ramp-incremental cardiopulmonary exercise test (CPX) on a cycle ergometer (5–10 W/min) to determine $\dot{V}O_2$ at peak exercise. These loads were individually adjusted according to the severity of symptoms and the severity of the disease. On a separate day, subjects performed a high-intensity constant work rate (CWR) trial test at 80% peak workrate (WR) to individually select PAV's flow and volume assist levels. At a subsequent experimental visit, the patients undertook, 1 h apart, two CWR at the previously defined WR to the limit of tolerance (*Tlim,* s*)*. Data were also recorded during the 5-min of passive recovery (without any muscle contraction), which followed exercise. During these tests, patients were randomly assigned to receive sham ventilation and the pre-selected levels of PAV. The patients and the accompanying physician were unaware of the ventilation strategy (PAV or sham) under use. This was accomplished by visually isolating the ventilator and its monitor from both the physician's and the patient's view. Vastus lateralis muscle oxygenation levels were assessed by NIRS. In addition, systemic O_2 delivery was followed by continuous monitoring of exercise cardiac output (transthoracic impedance) and metabolic and ventilatory measurements were collected breath-by-breath.

Non-invasive Positive Pressure Ventilation

PAV was applied *via* a tight-fitting facial mask with pressure levels being delivered by a commercially available mechanical ventilator (Evita-4; Draeger Medical, Lübeck, Germany). PAV is a non-invasive modality that provides flow (FA, cmH_2O

L^{-1} s^{-1}) and volume assistance (VA, cmH_2O/L) with the intent of unloading the resistive and elastic components of the work of breathing. PAV levels were individually set on a preliminary visit using the "run-away" method: the protocols for adaptation at rest and exercise were as previously described (Younes, 1992; Bianchi et al., 1998; Carrascossa et al., 2010). Sham ventilation was applied *via* the same equipment using the minimal inspiratory pressure support of 5 cmH_2O; moreover, 2 cmH_2O of positive end-expiratory pressure was used to overcome the resistance of the breathing circuit (Borghi-Silva et al., 2008a,b). Both PAV and sham were delivered with an O_2 inspired fraction of 0.21.

Maximal and Submaximal Cardiopulmonary Exercise Testing

Symptom-limited CPX was performed on a cycle ergometer using a computer-based exercise system ($CardiO_2$ System™ Medical Graphics, St. Paul, MN). Breath-by-breath analysis ventilatory expired gas analysis was obtained throughout the test. Incremental adjustment of work rate was individually selected (usually 5–10 W/min). The load increment was individually selected based on the symptoms of dyspnea reported by the patient for some physical activities and the experience of the research team. In patients with more severe symptoms such as dyspnea to walk on level ground, the load increase was 5 W, while those who did not report fatigue for this activity, an increase of 10 W was selected, which is considered to test completion ideally between 8 and 12 min (Neder et al., 1999). The carbon dioxide (CO_2) and O_2 analyzers were calibrated before and immediately after each test using a calibration gas (CO_2 5%, O_2 12%, and N_2 balance) and a reference gas [room air after ambient temperature and pressure saturated (ATPS) to standard temperature and pressure, dry (STPD) correction]. A Pitot tube (Prevent Pneumotach™, MGC) was calibrated with a 3-L volume syringe by using different flow profiles. As a bi-directional pneumotachograph based on turbulent flow, the Pitot tube was adapted at the opening of the mask used for non-invasive ventilation.

The following data were recorded: $\dot{V}O_2$ (ml/min), $\dot{V}CO_2$ (ml/min), minute ventilation ($\dot{V}_E$, L/min), and the partial pressure of end-tidal CO_2 ($P_{ET}CO_2$) (mmHg). Ventilatory efficiency ($\dot{V}_E/\dot{V}CO_2$ slope) was defined as the ventilatory response relative to CO_2 production. The $\dot{V}_E/\dot{V}CO_2$ slope provides the ventilatory requirements to wash out metabolically produced CO_2 (Keller-Ross et al., 2016). Peak $\dot{V}O_2$ was the highest 15-s averaged value at exercise cessation (Neder et al., 1999). In addition, 12-lead electrocardiographic monitoring was carried out throughout testing. Subjects were also asked to rate their "shortness of breath" at exercise cessation using the 0–10 Borg's category-ratio scale, and symptom scores were expressed in absolute values and corrected for exercise duration. Capillary samples were collected from the ear lobe for blood lactate measurements (mEq/L) at rest and at exercise cessation (Yellow Springs 2.700 STAT plus™, Yellow Springs Instruments, OH, United States).

Skeletal Muscle Oxygenation

Skeletal muscle oxygenation profiles of the left *vastus lateralis* were evaluated using a commercially available NIRS system (Hamamatsu NIRO 200™, Hamamatsu Photonics KK, Japan) during the CWR tests with PAV and sham (Borghi-Silva et al., 2008b). Previously, the skin under the probe was shaved in the dominant thigh. The skinfold was < 12.5 mm in all patients to ensure that the amount of fat between the muscle probe did not interfere with the signals (van der Zwaard et al., 2016). The light probe was placed to the belly of the vastus lateralis muscle, approximately 15 cm from the upper edge of the patella, and firmly attached to the skin using adhesive tape (Goulart et al., 2020b) and involved in a black closed mesh with a velcro. Briefly, one fiberoptic bundle carries the NIR light produced by the laser diodes to the tissue of interest while a second fiberoptic bundle returns the transmitted light from the tissue to a photon detector in the spectrometer. The intensity of incident and transmitted light is recorded continuously and, together with the relevant specific extinction coefficients, used for online estimation and display of the changes from the resting baseline of the concentrations of [deoxy-Hb + Mb] (Borghi-Silva et al., 2008b). [Deoxy-Hb + Mb] levels were obtained second-by-second at rest, during exercise, and 5 min of recovery. [Deoxy-Hb + Mb] has been used as a proxy of fractional O_2 extraction in the microcirculation, reflecting the balance between O_2 delivery and utilization (Sperandio et al., 2009). In order to reduce intrasubject variability and improve intersubject comparability, [deoxy-Hb + Mb] values were expressed as the percentage of the maximal value determined on a post-exercise maximal voluntary contraction (MVC) after 5-min recovery. This study used a single probe consisting of eight laser diodes operating at two wavelengths (690 and 830 nm). Due to the uncertainty of the differential pathlength factor (DPF) for the quadriceps, we did not use a DPF in the present study. The distance between the light emitters and the receiver was 3.5 cm (Goulart et al., 2020b).

Central Hemodynamics

Cardiac output (Q_T, L/min) was measured using a calibrated signal-morphology impedance cardiography device (PhysioFlow PF-05, Manatec Biomedical, France). The PhysioFlow principle is based on the assumption that variations in impedance occur when an alternating current of high frequency (75 kHz) and low magnitude (1.8 mA) passes through the thorax during cardiac ejection (Borghi-Silva et al., 2008a). In preliminary experiments, the system detected small changes in Q_T ($\sim$0.1 L/min) with acceptable accuracy (within $\pm$ 10% for all readings) (Borghi-Silva et al., 2008a). The values were recorded as delta (Δ) from baseline and expressed relative (%) to the amplitude of variation from baseline to the steady-state with sham ventilation (within $\pm$ 2 standard deviations of the local mean).

Kinetics Analysis

Breath-by-breath $\dot{V}O_2$, Δ[deoxy-Hb + Mb], HR, and Q_T data were time aligned to the cessation of exercise and the first 180 s of recovery were interpolated second by second (SigmaPlot 10.0 Systat Software Inc., San Jose, CA, United States). Data were analyzed from the last 30 s of exercise to obtain a more stable baseline and over the 180 s of recovery; i.e., it is considered only the primary component of the response. Using this approach, it was assured that the same amount of data was included in the kinetic analysis of $\dot{V}O_2$, Δ [deoxy-Hb + Mb], and Q_T for each intervention, minimizing model-dependent effects on results. The model used for fitting the kinetics response was:

$$[Y](t) = [Y](ss) --A \cdot \left(1 - e^{-(t-TD\rho)/\tau}\right) \quad (1)$$

where the subscripts "ss" and "ρ" refer to steady-state and primary component, respectively. "A," "TD," and "τ" are the amplitude, time delay, and time constant of the exponential response of the interest (i.e., ~time to reach 63% of the response following the end of exercise), respectively. The overall kinetics of Δ[deoxy-Hb + Mb] were determined by the mean of response time (MRT = τ + TD) (Mazzuco et al., 2020).

Statistical Analysis

The required number of patients to be assessed (n = 10, crossover study) was calculated considering the τ (s) of $\dot{V}O_2$ during PAV and sham in HF patients as the main outcome (Mazzuco et al., 2020), assuming a risk of α of 5% and β of 20%. The SPSS version 13.0 statistical software was used for data analysis (SPSS, Chicago, IL, United States). According to data distribution, results were reported as mean ± SD or median and ranges for symptom scores. The primary end point of the study was changes in MRT-[deoxi-Hb + Mb] with PAV compared to sham. Secondary end points included Tlim, changes of τ $\dot{V}O_2$, and Q_T recovery kinetics. To contrast differences between PAV and sham on exercise responses and kinetic measurements, non-paired t or Mann–Whitney tests were used as appropriate. Pearson's product moment correlation was used to assess the level of association between continuous variables. The level of statistical significance was set at $p < 0.05$ for all tests.

RESULTS

All patients completed the maximal and submaximal exercise tests. Baseline characteristics of HFrEF patients are presented in **Table 1**. The LVEF ranged from 22 to 26%. Peak WR and $\dot{V}O_2$ of all patients were below the age- and gender-corrected lower limits of normality (Neder et al., 1999). Eight patients were Weber class C and two were class B. As anticipated by long-term β-blocker therapy, patients presented with a reduced peak HR response.

Physiological Responses at the Tlim After Sham vs. PAV

The values selected for volume and flow assist during PAV were 5.6 ± 1.4 cmH_2O/L and 3.0 ± 1.2 $cmH_2O\ L^{-1}\ s^{-1}$, respectively. PAV significantly improved exercise tolerance as shown by a longer *Tlim* compared to sham ventilation ($p < 0.05$, **Table 2**). There was no significant change in $\dot{V}O_2$ at *Tlim*; however, a significantly higher $\dot{V}CO_2$ was observed with PAV ($p < 0.05$, **Table 2**). In addition, ventilatory efficiency improved with PAV as demonstrated by a significant reduction in $\dot{V}_E/\dot{V}CO_2$ slope compared to sham ventilation ($p < 0.05$, **Table 2**).

Off-Exercise Dynamics After Sham and PAV

All fitted data were included in the kinetics analysis as r^2-values ranged from 0.90 to 0.99. Off-exercise PAV accelerated $\dot{V}O_2$ kinetics when compared to sham ventilation (representative subject in **Figure 1A** and sample values in **Table 3**). In parallel, Q_T recovery kinetics was faster with PAV (**Figure 1B** and **Table 3**) ($p < 0.05$). The accelerated Q_T kinetics was largely explained by a faster HR recovery with PAV (**Table 3**). Similar speeding effects of PAV were observed in relation to [deoxy-Hb + Mb] (**Figure 1C** and **Table 3**). Consistent with these results, $\dot{V}O_2$, Q_T, and [deoxy-Hb + Mb] MRT values were shorter with PAV compared to sham

TABLE 1 | Patient characteristics at rest, medication used, and cardiopulmonary exercise testing data (N = 10).

Anthropometric characteristics	
Age (years)	50 ± 13
Height (m)	1.67 ± 0.05
Body mass (kg)	74 ± 13
Body mass index (kg/m^2)	25 ± 3
Echocardiography	
LVEF (%)	26 ± 4
Etiology of heart failure	
Ischemic	3
Non-ischemic	7
Medications	
Diuretic	9
Digitalis	3
Carvedilol	10
Angiotensin-converting enzyme inhibitor	8
Maximal exercise	
Power, W	90 ± 27
Metabolic	
Peak $\dot{V}O_2$,% pred	55 ± 14
Peak $\dot{V}O_2$, ml min	1.222 ± 284
Peak $\dot{V}O_2$, ml min^{-1} kg^{-1}	17 ± 5
Peak $\dot{V}CO_2$, ml min	1.358 ± 436
Peak blood lactate (mmol/L)	4.0 ± 2.1
Ventilatory	
$\dot{V}_E$, L min^{-1}	47 ± 8.4
Respiratory rate, breaths min^{-1}	32 ± 8
V_T, L	1.60 ± 0.39
Cardiovascular	
Heart rate, bpm	116 ± 15
Heart rate,% pred	65 ± 5.8
Oxygen pulse (ml min^{-1}/bpm)	11 ± 1.5
Subjective	
Dyspnea scores	6 ± 2.0
Leg effort scores	6 ± 2.1

*LVEF, left ventricle ejection fraction of left ventricle; FEV_1, forced expiratory volume in 1 s; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide output; $\dot{V}_E$, minute ventilation; V_T, tidal volume, HR, heart rate. *Mean (SD).*

ventilation (**Figure 2**). The improvement in Q_T dynamics with active intervention was related to enhanced exercise tolerance ($p < 0.001$, **Figure 3**).

DISCUSSION

The novel findings of the present study in patients with stable, but advanced, HFrEF are as follows: (1) PAV improved exercise tolerance and ventilatory efficiency; (2) PAV accelerated the recovery of $\dot{V}O_2$, as well as [deoxy-Hb + Mb] (a non-invasive estimate of fractional O_2 extraction) (Barstow, 2019), and central hemodynamics; and (3) a faster recovery of central hemodynamics with PAV was associated with better exercise tolerance. These data indicate that unloading the respiratory muscles has positive effects on O_2 delivery to, and utilization by, the peripheral muscles during passive recovery from exercise in HFrEF. These results set the stage for future studies assessing a role for respiratory muscle unloading in enhancing the tolerance to repeated (interval) exercise in these patients.

Effects of PAV on Muscle Reoxygenation Kinetics

It is widely recognized that the skeletal muscle deoxygenation at the onset of exercise in patients with HFrEF is related to impairments of local O_2 delivery and utilization (Richardson et al., 2003). In addition, experimental evidence suggests that, as HFrEF progresses, there is a slower recovery of microvascular PO_2 ($PmvO_2$), reflected by impaired microvascular O_2 delivery-to-utilization matching in the active muscle, i.e., lower $PmvO_2$ (Copp et al., 2010). A lower $PmvO_2$, in turn, may impair the recovery of intracellular metabolic homeostasis, delaying phosphocreatine resynthesis after exercise in HFrEF. These important metabolic changes increase muscle fatigability, likely

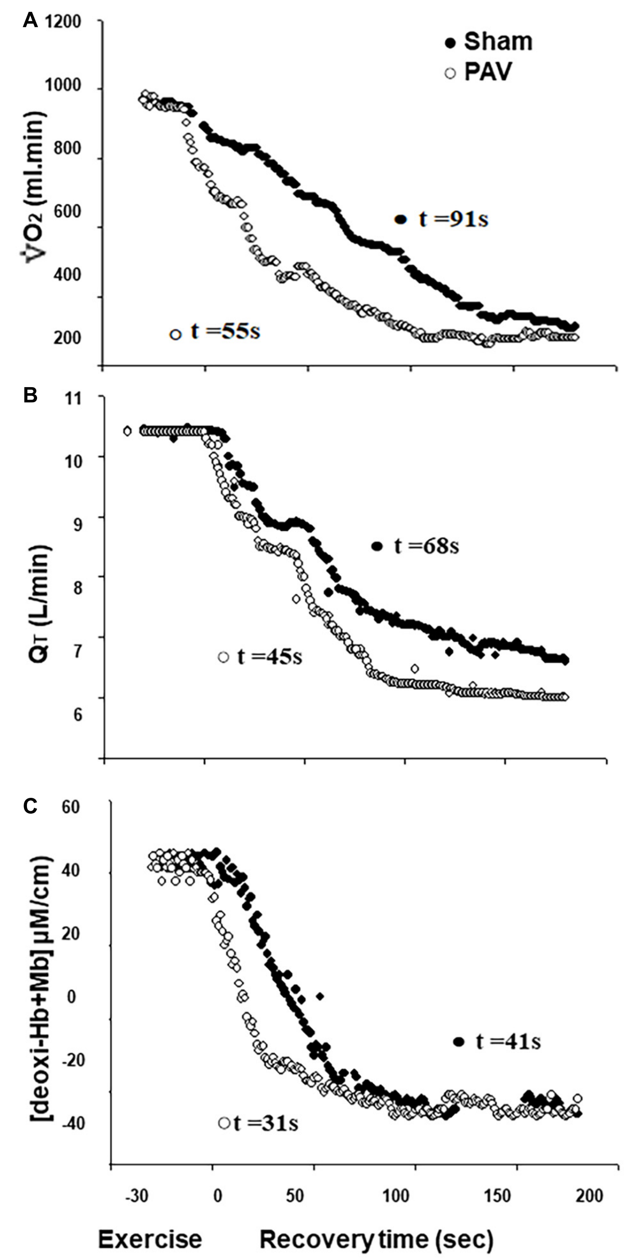

FIGURE 1 | Pulmonary O_2 uptake [$\dot{V}O_{2p}$, **(A)**], cardiac output [Q_T, **(B)**], and deoxy-hemoglobin concentration [deoxy-Hb + Mb, **(C)**] off-kinetics variables at high-intensity constant workload exercise test of a representative patient with HFrEF contrasting PAV (○) vs. Sham Ventilation (●).

impairing the ability to perform subsequent physical tasks (Krause et al., 2005; Copp et al., 2010). In this sense, ventilatory strategies that can reduce fatigability and increase muscle recovery for a new high-intensity task would be relevant for the cardiopulmonary rehabilitation of these patients. In addition, HFrEF may be associated with redistribution of an already-reduced cardiac output toward the respiratory muscles, leading to lower peripheral muscle perfusion and O_2 supply. Collectively,

TABLE 2 | Main physiological responses at the time of constant work rate exercise tolerance (Tlim) after sham or proportional assist ventilation (*N* = 10).

	Sham	PAV	*p*-value
Tlim (s)	444 ± 296	587 ± 390	0.01
$\dot{V}O_2$ (ml/min)	1, 183 ± 450	1, 280 ± 285	0.40
$\dot{V}CO_2$ (ml/min)	1, 153 ± 287	1, 258 ± 257	0.03
RER	1.02 ± 0.08	1.02 ± 0.36	0.96
$\dot{V}_E$ (L/min)	44.6 ± 7.1	45.6 ± 6.4	0.67
$\dot{V}_{E}/CO_2$ slope	40.3 ± 10.7	37.1 ± 7.6	0.04
$P_{ET}CO_2$, mmHg	32.1 ± 7.5	33.3 ± 7.1	0.54
HR, bpm	109 ± 11	110 ± 15	0.70
HR,% peak	63 ± 6	64 ± 7	0.72
Oxygen pulse (ml/min/beat)	10.8 ± 4.4	11.7 ± 2.6	0.42
Dyspnea (0–10)	5.7 ± 1.4	5.1 ± 1.7	0.19
Leg effort (0–10)	5.9 ± 3.0	5.4 ± 2.5	0.49
Δlactate (peak-rest, mmol/L)	2.10 ± 1.16	1.88 ± 1.14	0.67

$\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide output; RER, respiratory exchange ratio; $\dot{V}_E$, minute ventilation; $P_{ET}CO_2$, end-tidal partial pressure for CO_2; HR, heart rate. $p < 0.05$ (paired t or Wilcoxon tests for between-group differences at a given time point). Values are means ± SD.

TABLE 3 | Off-exercise kinetic parameters for oxygen uptake ($\dot{V}O_{2p}$), [deoxy-Hb/Mb], and cardiac output (Q_T) after sham or proportional assist ventilation (PAV) (*N* = 10).

Variables	Sham	PAV	*P*-level
$\dot{V}O_{2p}$			
Baseline (ml)	1,224 ± 272	1,205 ± 289	0.12
A (ml)	952 ± 242	882 ± 235	0.76
τ (s)	77 ± 42	56 ± 22	0.04
Q_T			
Baseline (ml)	10 ± 2	10 ± 1	0.22
A (ml)	5 ± 1	5 ± 1	0.15
τ (s)	78 ± 46	39 ± 22	0.02
HR			
Baseline (ml)	109 ± 10	109 ± 15	0.95
A (ml)	31 ± 11	29 ± 7	0.48
τ (s)	54 ± 23	35 ± 13	0.01
MRT (s)	63 ± 22	41 ± 17	0.003
[deoxy-Hb + Mb]			
Baseline (ml)	53 ± 29	54 ± 30	0.86
A (ml)	78 ± 37	67 ± 26	0.55
τ (s)	42 ± 22	31 ± 19	0.04

Values are means ± SD. Definition of symbols and abbreviations: TD, time delay; τ, time constant. $\dot{V}O_{2p}$, Pulmonary oxygen uptake, Q_T, cardiac output, MRT, mean response time, [deoxy-Hb/Mb], deoxyhemoglobin + myoglobin concentration by NIRS.

these abnormalities may impair leg muscles' oxidative capacity with negative effects on dyspnea, leg discomfort, and exercise tolerance in these patients (Poole et al., 2012).

In the present study, PAV accelerated the recovery of leg muscle oxygenation, as indicated by a faster decrease in [deoxy-Hb + Mb] (**Table 3** and **Figure 2**). The explanation for this finding might be multifactorial. For instance, PAV may have increased peripheral vascular conductance *via* lower sympathetic outflow (Olson et al., 2010) in response to a lessened respiratory muscle metaboreflex (Sheel et al., 2018). In fact, this was previously shown that at a given Q_T and time, PAV was associated with increased oxygenation and higher blood flow to the appendicular musculature in patents with HFrEF, suggesting blood flow redistribution (Borghi-Silva et al., 2008b). Of note, Miller et al. found that decreasing the work of breathing with inspiratory positive pressure ventilation increased hindlimb blood flow out of proportion to increases in cardiac output in dogs with experimental HFrEF (Miller et al., 2007). Thus, bulk blood flow to the legs may have been enhanced by PAV despite a faster decrease in Q_T, which would tend to *reduce* convective O_2 delivery at a given time point. The positive effects of PAV on muscle blood flow during high-intensity exercise may have persisted throughout the recovery phase, leading to more pronounced post-exercise hyperemia (Goulart et al., 2020a).

A preferential distribution of local blood flow toward type II fibers, which are less efficient on O_2 utilization compared to type I fibers, is also conceivable (Barstow et al., 1996; Poole et al., 2012). Another possible mechanism demonstrated is that under hypoxia conditions, [deoxy-Hb + Mb] occurs at a lower energy output (Rafael de Almeida et al., 2019). It should also be acknowledged that the positive effects of PAV on on-exercise $\dot{V}O_2$ kinetics (i.e., low O_2 deficit) may have decreased O_2 debt, leading to a faster decrease in off-exercise $\dot{V}O_2$ (Mazzuco et al., 2020). Consistent with the current findings, this study found that respiratory muscles unloading reduced leg fatigue during high-intensity isokinetic exercise, supporting evidence that this strategy might have an adjunct role to improve patients' response to rehabilitative exercise in HFrEF (Borghi-Silva et al., 2009).

The QT off-kinetics were also accelerated with PAV (**Table 3** and **Figure 1**). This might be related to the fact that PAV was associated with lower O_2 demands during recovery, likely due to improved muscle bioenergetics, i.e., faster PCr resynthesis (Yoshida et al., 2013). Additionally, a lower sympathetic drive with non-invasive ventilation may have prompted a faster increase in parasympathetic tonus (Borghi-Silva et al., 2008c); in fact, the quicker decrease in Q_T was largely secondary to a faster HR recovery (**Table 3**). Interestingly, a strong correlation between faster Q_T decline and increases in Tlim with PAV was found (**Figure 3**). Again, this might reflect a larger decrease in sympathetic efference in patients who derived greater benefit from PAV. Additional studies quantifying sympathetic neural outflow at similar exercise duration with PAV and sham ventilation are warranted to confirm (or negate) this hypothesis (Borghi-Silva et al., 2008c; Reis et al., 2014).

PAV and Ventilatory Efficiency in HFrEF

The present study found that respiratory muscle unloading with PAV was associated with improved ventilatory efficiency, i.e., lower $\dot{V}_E$–$\dot{V}CO_2$ relationship (**Table 2**). Of note, however, this was not a consequence of lower $\dot{V}_E$ at a given $\dot{V}CO_2$, but rather similar $\dot{V}_E$ *despite* a higher $\dot{V}CO_2$. Higher $\dot{V}CO_2$ (and, to a lesser extent, $\dot{V}O_2$) at exercise cessation with PAV than sham might reflect the effects of a longer test in the former intervention during the PAV trial. This may also occur due to the dynamics of $\dot{V}CO_2$ and its relationship with the kinetics of CO_2 storage and production (Scott Bowen et al., 2012).

It remains unclear, however, why $\dot{V}_E$ remained unaltered despite a higher CO_2 "load" since the respiratory neural drive, lung mechanics, or ventilation/perfusion (mis)matching was not assessed. Regardless of the mechanism, a reduction in the $\dot{V}_E$–$\dot{V}CO_2$ through pharmacological and non-pharmacological interventions may have relevant clinical implications, including improved survival (Paolillo et al., 2019). It is worth noting that dyspnea ratings at Tlim were similar between conditions despite a longer Tlim with PAV (**Table 2**). This might reflect the effects of an unaltered $\dot{V}_E$ and/or the beneficial consequences of inspiratory muscle unloading.

Methodological Considerations and Potential Limitations

The present study focused on the effects of PAV on recovery kinetics since the presence of oscillatory ventilation in half of patients precluded the analysis of on-exercise $\dot{V}O_2$ kinetics (Sperandio et al., 2009). Consistent with these results, previous studies showed that recovery kinetics were more reproducible, being determined with a higher degree of reliability and validity

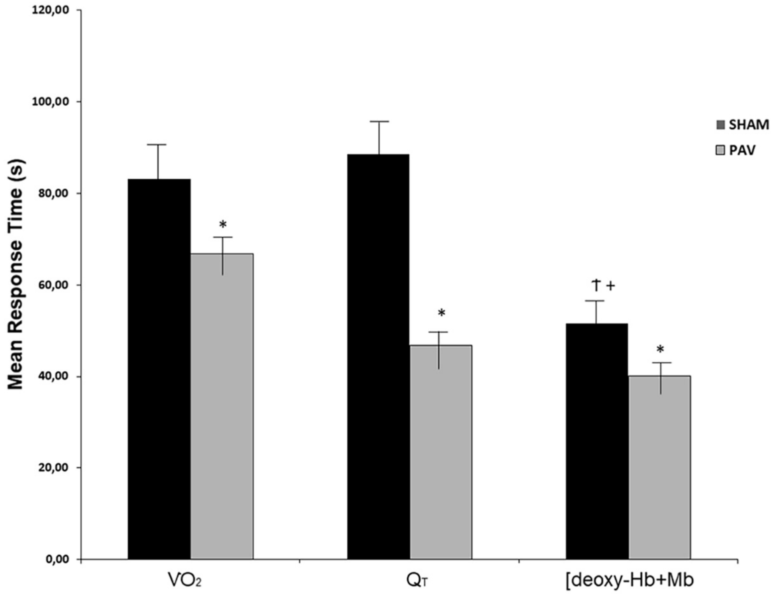

FIGURE 2 | Mean response time (MRT) of $\dot{V}O_{2p}$, Q_T, and deoxy-hemoglobin concentration ([deoxy-Hb + Mb]), on recovery of heavy-intensity exercise during Sham (open bars) and PAV (solid bars). Note that the dynamics of $\dot{V}O_{2p}$ and Q_T and [deoxy-Hb + Mb] recovery were faster during PAV ($p < 0.05$). In addition, [deoxy-Hb + Mb] kinetic was faster than QT and $\dot{V}O_{2p}$ only when Sham was administered in HFrEF patients. Values are means (SD). *$p < 0.05$ for between-intervention comparisons; $^{\dagger}p < 0.05$ for within-variables comparisons between [deoxy-Hb + Mb] vs. $\dot{V}O_{2p}$; and $^{+}p < 0.05$ for within-group comparisons of [deoxy-Hb + Mb] vs. Q_T.

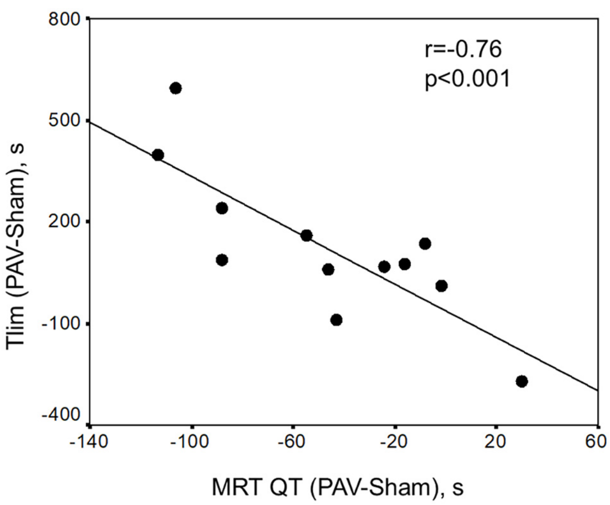

FIGURE 3 | Significant inverse relationship between the difference of limit of tolerance with PAV-Sham vs. the difference of mean response time (MRT) of QT (PAV-Sham). These data suggest that the higher variation of Tlim with PAV, the faster lower "central" cardiovascular kinetics (Pearson correlation = 0.76, $p < 0.001$).

(Kemps et al., 2009, 2010). Nevertheless, the present study acknowledges that by not repeating the exercise bout, it is limited in its ability to determine the actual beneficial effects of PAV on the tolerance of any ensuing exercise. It is reasoned that a second session could influence [deoxy-Hb + Mb] due to changes in probe position, thereby decreasing the between-days comparability. Moreover, this study did not measure the work of breathing; thus, the magnitude of respiratory muscle unloading brought by PAV in individual patients remains unclear. As a non-invasive study, it relied on signal-morphology cardioimpedance to measure Q_T (Borghi-Silva et al., 2008a; Paolillo et al., 2019). Although this method is not free from caveats (Wang and Gottlieb, 2006), it has provided acceptable estimates of changes in Q_T in patients with cardiopulmonary diseases (Vasilopoulou et al., 2012; Louvaris et al., 2019).

Clinical Implications

The findings of the present study indicate that respiratory muscle unloading improves muscle oxygenation during recovery from high-intensity exercise, suggesting that non-invasive ventilation (PAV) might be used as an adjunct strategy to improve the tolerance to subsequent exercise during cardiac rehabilitation. Future studies could investigate the effects of such strategy in cardiopulmonary rehabilitation programs. It is conceivable that such an effect would be particularly relevant to more severe patients exposed to interval training (Spee et al., 2016) or, as described before, to strength training (Borghi-Silva et al., 2009). If the beneficial effects of PAV on muscle oxygenation prove to be associated with improved autonomic modulation (lower sympathetic drive), long-term respiratory muscle unloading may have an hitherto unexplored effect on other relevant outcomes in HFrEF, such as ventricular tachyarrhythmias, cardiac remodeling, and left ventricle afterload (Cornelis et al., 2016).

CONCLUSION

Respiratory muscle unloading promoted by PAV improves leg muscle oxygenation during the recovery from high-intensity exercise in patients with HFrEF. These results add novel evidence that the salutary consequences of PAV on the physiological responses to dynamic exercise in HFrEF (Borghi-Silva et al., 2008a,b; Carrascossa et al., 2010) extend to the recovery phase, an effect that might be of practical relevance to improve tolerance to repeated (interval) exercise.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation in the Institutional Repository of UFSCar.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the CEP 0844/06. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

AB-S, CG, CC, CO, DB, DA, LN, RA, and JN: conceptualization, data curation, formal analysis, investigation, methodology, project administration, supervision, writing—original draft, and writing—review and editing. All authors contributed to the article and approved the submitted version.

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Peak Running Velocity or Critical Speed Under Field Conditions: Which Best Predicts 5-km Running Performance in Recreational Runners?

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This study aimed to examine which variable, between the peak running velocity determined on the track field (V_{peak_TF}) and critical speed (CS), is the best predictor of the 5-km running performance in recreational runners. Twenty-five males performed three tests to determine the V_{peak_TF}, CS, and 5-km running performance on the track field, with a minimal interval of 48 h between each test. The V_{peak_TF} protocol started with a velocity of 8 km·h^{-1}, followed by an increase of 1 km·h^{-1} every 3 min until volitional exhaustion, which was controlled by sound signals, with cones at every 25 m indicating when the participants were required to pass the cone's position to maintain the required velocity. The participants performed three time trials (TTs) (1: 2,600 m; 2: 1,800 m; and 3: 1,000 m) on the same day, with a 30-min rest period to determine the CS through the combinations of three ($CS_{1,2,3}$) and two TTs ($CS_{1,2}$, $CS_{1,3}$, and $CS_{2,3}$). The 5-km running performance time was recorded to determine the test duration, and the mean velocity (MV) was calculated. There was a significant difference observed between the V_{peak_TF} and the MV 5-km running performance. However, no differences were found between the CS values and the MV 5-km running performance. A correlation was observed between the V_{peak_TF} ($R = -0.90$), $CS_{1,2,3}$ ($R = -0.95$), $CS_{1,3}$ ($R = -0.95$), and the 5-km running performance time. Linear regression indicated that the V_{peak_TF} ($R^2 = 0.82$), $CS_{1,2,3}$ ($R^2 = 0.90$), and $CS_{1,3}$ ($R^2 = 0.90$) significantly predicted the 5-km running performance time. The CS results showed a higher predictive power for the 5-km running performance, slightly better than the V_{peak_TF}. Also, $CS_{1,2,3}$ and the $CS_{1,3}$ presented the highest predictive power for the 5-km running performance of recreational runners.

Keywords: prediction, performance, running, endurance, exercise test

INTRODUCTION

Millions of recreational runners participate in long-distance running competitions (i.e., 5 and 10 km) each year, being consistently considered among the most popular distances and with the greatest number of competitions, even greater than marathons (Cushman et al., 2014; Vickers and Vertosick, 2016). Therefore, it is important to apply test protocols that assess the aerobic capacity to accurately predict the running performance, to which aerobic metabolism contributes about 95% of the total energy expenditure (Busso and Chatagnon, 2006). It is possible through these test protocols to be able to identify the physiological and performance variables that might be used to improve the prediction of the runners' performances, such as the maximal oxygen uptake ($\dot{V}O_{2max}$), the velocity of $\dot{V}O_{2max}$ occurrence ($v\dot{V}O_{2max}$), running economy (RE), the responses associated with the blood lactate concentrations during exercise [i.e., lactate threshold (LT), anaerobic threshold (AnT), and maximal lactate steady state (MLSS)], peak running velocity (V_{peak}), and critical speed (CS) (Machado et al., 2013; da Silva et al., 2015; Nimmerichter et al., 2016).

Among these variables, the V_{peak} and CS stand out, which can be determined in simple, objective, and sensitive protocols that do not require the use and handling of expensive and delicate equipment or invasive techniques, considered accessible and of great practical application (Jones and Poole, 2009).

V_{peak} is defined as the highest effort intensity achieved during an incremental test until the maximum volitional exhaustion (Noakes et al., 1990), which is considered a strong predictor of endurance running performance and presents high correlation with the 3–90 km events (Slattery et al., 2006; Stratton et al., 2009; Machado et al., 2013). For instance, Machado et al. (2013) reported high correlation ($R = 0.95$) and predictive power ($R^2 = 0.91$) between the V_{peak} determined on the incremental treadmill test protocol (V_{peak_T}) with a 3-min stage duration, defined according to Kuipers et al. (2003), and the 5-km running performance of recreational runners.

CS represents the intensity of effort (e.g., running speed) that can be maintained for an extended period (≈30–60 min) without a continual rise in systemic [e.g., blood lactate concentration (La) and oxygen uptake ($\dot{V}O_2$)] and intramuscular metabolism (e.g., pH and phosphocreatine concentration) homeostasis (Jones et al., 2008, 2010; Poole et al., 2016; Jones and Vanhatalo, 2017). This concept is based on the hyperbolic relation between the predetermined intensities of effort (i.e., distance or running speed) and the time it takes to reach exhaustion (i.e., time limit- t_{lim}) (Hughson et al., 1984; Hill, 1993). Previous studies have also investigated the use of CS for running performance prediction in distances ranging from 40 m to longer distances such as that of a marathon (Kranenburg and Smith, 1996; Florence and Weir, 1997; Nimmerichter et al., 2016). A recent study involving trained endurance athletes has observed higher correlations ($R = -0.79$ and 0.82) and predictive power ($R^2 = 0.64$ and 0.67) between the CS estimated on the treadmill test protocol performed on the same day with time and the mean velocity (MV) 5-km running performance, respectively, suggesting that CS is valuable for predicting performance compared to $\dot{V}O_{2max}$ (Nimmerichter et al., 2016).

Nevertheless, to predict the endurance of running performances, the determination of V_{peak_T} and the estimation of CS were exclusively performed under laboratory conditions (Stratton et al., 2009; Machado et al., 2013; Nimmerichter et al., 2016), which do not provide ecological validity due to the different characteristics of a treadmill and track field running regarding propulsion, overcoming air resistance, inertia, and gait pattern that might affect the utilization of treadmill-derived measures into field conditions (Van Caekenberghe et al., 2013). Tests performed on a track field are more applicable due to the higher specificity to the sports' performance, which can be easily integrated into a daily training routine and, therefore, are less time-consuming than laboratory tests. Furthermore, the development of knowledge concerning the prediction of the 5-km running performance that underlies these variables present on the track field will enable greater specificity on the prescription of training intensities and could also provide practitioners and their coaches the optimal pacing and tactical strategies that will allow improvements on their competitive results.

At the moment, there is no consensus on the best predictor variable (V_{peak} or CS) contributor determined on the track field relative to the 5-km running performance. Thus, this study aimed to examine which variable, between the peak running velocity determined on the track field (V_{peak_TF}) and the critical speed (CS), is the best predictor of the 5-km running performance in recreational runners. The study's hypothesis is that V_{peak_TF} has a higher predictive power for the 5-km running performance than does the CS, given that V_{peak} is the "determined" velocity associated with the $\dot{V}O_{2max}$ established through an incremental protocol, while CS is "estimated" through linear regression using mathematical models with a constant distance path protocol.

MATERIALS AND METHODS

Participants

Twenty-five male recreational runners, regional and local level competitors (mean ± SD: age = 28.6 ± 4.7 years, height = 176.2 ± 9.7 cm, body mass = 78.5 ± 10.4 kg, relative lean mass = 89.3 ± 4.5%, relative adipose mass = 10.7 ± 4.5%), with a 5-km running performance time of 25.3 ± 3.0 min and MV of 12.0 ± 1.3 km·h^{-1} (which represented 49.8% of the MV from the world record) were recruited as the participants in this study.

All participants were physically active with a training running experience of at least 2 years and had a training frequency of 3.0 ± 0.7 days·week^{-1}, with an average distance of 24.4 ± 7.3 km·week^{-1}. They presented medical clearance to perform exhaustive physical tests and reported no use of nutritional ergogenic supplements for the duration of the study. To include the participant's data in the final analysis, the following requirement was adopted: Presenting a 5-km running performance time between 21.4 and 32.6 min (Machado et al., 2013; Vickers and Vertosick, 2016; Peserico et al., 2019). The participants were informed that they were free to withdraw from the study at any time. Prior to testing, a written consent form was obtained from all participants. The experimental protocol was approved by the local Human Research Ethics Committee (no. 2.698.091/2018).

Design

After the familiarization process with the track field test protocols, each participant performed three randomly ordered tests to determine the V_{peak_TF}, the CS, and the 5-km running performance on the official outdoor track field (400 m) at the same time of the day under similar climatic conditions (temperature = 25–29 °C and relative humidity = 60–75%), with an interval of 48 h between each test. They were instructed to report for testing well rested, well hydrated, and wearing lightweight comfortable clothing and also to avoid eating 2 h before the maximal exercise tests, to abstain from caffeine and alcohol, and to refrain from strenuous exercise for 24 h before testing (Machado et al., 2013). All of the participants were verbally encouraged throughout the tests, and mineral water was provided *ad libitum* so that the participants could hydrate themselves, as they were used to do in long-distance races.

Determination of V_{peak} on the Track Field

The protocol used to determine V_{peak_TF} was the same one used for the determination of V_{peak_T} (Machado et al., 2013). After a warm-up, consisting of walking at 6 km·h^{-1} for 3 min, the protocol started with an initial velocity of 8 km·h^{-1}, followed by an increase of 1 km·h^{-1} every 3 min (Machado et al., 2013). The velocity during the protocol on the track field was controlled by sound signals, with cones at every 25 m, indicating when the participants were required to pass the cone's position to maintain the required velocity (Léger and Boucher, 1980). The protocol ended when the participants reached volitional exhaustion (i.e., the participant was unable to continue running) or when the evaluator identified that the participants failed to cross the cone line with one of two feet on three consecutive occasions (Léger and Boucher, 1980). If the last stage was not completed, V_{peak_TF} was calculated with the partial time remaining in the last stage according to the equation: $V_{peak\_TF} = V_{complete} + (\text{Inc} \times t/T)$, where $V_{complete}$ is the running velocity of the last complete stage, Inc is the velocity increment (i.e., 1 km·h^{-1}), t is the number of seconds sustained during the incomplete stage, and T is the number of seconds required to complete a stage (i.e., 180 s) (Kuipers et al., 2003).

Determination of Critical Speed

Each participant performed three time trials (TTs) on the track field (1: 2,600 m; 2: 1,800 m; and 3: 1,000 m). These TTs were selected according to Galbraith et al. (2011) and Hughson et al. (1984) to result in completion times between 3 and 12 min before volitional exhaustion. Consistent with Triska et al. (2017) and Galbraith et al. (2011), the sequence of TTs was conducted in the order of the longest to the shortest effort, on the same day, with a 30-min rest period to ensure a fully reconstituted D' (maximum distance covered above the CS). The participants completed a 5-min self-paced low-intensity warm-up exercise and were encouraged to cover the set TTs as quickly as possible; time was measured using a stopwatch (Galbraith et al., 2014). The CS was estimated through a linear regression between the distance run (d) and t_{lim} using the $d = (\text{CS} \times t_{lim}) + D'$ model, where d is the distance run (in meters), CS the critical speed (in meters per second), t_{lim} the time to exhaustion (in seconds), and D' is the maximum distance covered (in meters) above the CS (Hughson et al., 1984; Galbraith et al., 2011). CS was estimated through the combinations of three ($CS_{1,2,3}$) and two TTs ($CS_{1,2}$, $CS_{1,3}$, and $CS_{2,3}$).

5-km Running Performance

The 5-km running performance was preceded by a self-selected warm-up of 10 min. The participants freely choose their pacing strategy during this performance and were encouraged to cover the set distance as quickly as possible on the track field. The 5-km running performance time for each participant was recorded and registered by the evaluator using a stopwatch to determine the test duration, and MV was calculated by dividing the total distance by the trial duration. No information on the elapsed time was provided for the participants.

Statistical Analysis

The Statistical Package for the Social Sciences (SPSS® v25.0 for Windows, Inc., Chicago, IL, United States) was used to conduct the analysis. The normality assumption was verified using the Shapiro–Wilk test, and the results are presented as the mean ± SD. Sphericity was tested using Mauchly's test. Greenhouse–Geisser corrections were made when the assumptions of sphericity were violated. One-way ANOVA for repeated measures followed by Bonferroni *post hoc* test was used to evaluate the differences between V_{peak_TF} and CS that resulted from the different time trial (TT) combinations and the 5-km running performance. Separate linear regression models were fit to establish Pearson's product-moment correlations (R), coefficients of determination (R^2), and the standard error of the estimate (SEE) to examine the goodness of fit of the univariate relation between the V_{peak_TF} and CS that resulted from the different TT combinations (independent variables) and the 5-km running performance (dependent variable). The correlation coefficients (R) were interpreted using the following qualitative descriptors: Trivial (<0.1), small (<0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), nearly perfect (>0.9), and perfect (1.0) (Hopkins et al., 2009). Absolute agreement and the overall mean bias between $CS_{1,2,3}$ with $CS_{1,2}$, $CS_{1,3}$, and $CS_{2,3}$ were determined using limits of agreement (LoA) analysis (Bland and Altman, 1986). Furthermore, SEE was also calculated to show any error between the CS results from the different TT combinations. The significance level was set at $P < 0.05$ for all statistical analyses.

RESULTS

The V_{peak_TF}, the CS values estimated from the different TT combinations, and the MV for the 5-km running performance are shown in **Table 1**. There were significant differences between

TABLE 1 | Mean ± SD and range obtained from the V_{peak_TF}, CS values estimated through different TT combinations, and the MV for the 5-km running performance ($n = 25$).

Variable	Mean ± SD (km·h^{-1})	Range (km·h^{-1})
V_{peak_TF}	13.7 ± 1.1	11.0–15.9
$CS_{1,2,3}$	12.1 ± 1.4*	8.6–13.8
$CS_{1,2}$	12.5 ± 1.7*	8.0–15.4
$CS_{1,3}$	12.1 ± 1.4*	8.7–13.8
$CS_{2,3}$	11.7 ± 1.4*	7.4–13.7
MV 5-km running performance	12.0 ± 1.3*	9.2–14.1

V_{peak_TF}, Peak running velocity determined on the track field; $CS_{1,2,3}$, Critical speed at 2,600, 1,800 and 1,000 m; $CS_{1,2}$, Critical speed at 2,600 and 1,800 m; $CS_{1,3}$, Critical speed at 2,600 and 1,000 m; $CS_{2,3}$, Critical speed at 1,800 and 1,000 m; MV, Mean velocity.
**$P < 0.001$ in relation to V_{peak_TF}.*

the V_{peak_TF} and CS values and the MV for the 5-km running performance. However, there were no differences between the CS values as well as between the CS values with MV for the 5-km running performance.

Figure 1 shows the relation between each independent variable (the V_{peak_TF} and CS values estimated from the different TT combinations) and the 5-km running performance time. The V_{peak_TF} ($R = -0.90$) and the CS ($R = -0.80$ to -0.95) values showed high and negative correlations with the 5-km running performance time. Linear regression analysis indicated that the V_{peak_TF}, $CS_{1,2,3}$, $CS_{1,2}$, $CS_{1,3}$, and $CS_{2,3}$ significantly predicted 82, 90, 70, 90, and 64% of the variance in the 5-km running performance time, respectively.

The Bland–Altman plots of the differences between $CS_{1,2,3}$ and $CS_{1,2}$, $CS_{1,3}$, and $CS_{2,3}$ are presented in **Figure 2**. The results revealed the highest agreement (i.e., the overall mean bias was least and the 95% LoA narrowest) in the comparison between $CS_{1,2,3}$ and $CS_{1,3}$. In comparison to $CS_{1,2,3}$, $CS_{1,3}$ showed a SEE of 0.08 km·h^{-1} and $CS_{1,2}$ and the $CS_{2,3}$ showed SEEs of 0.76 and 0.67 km·h^{-1}, respectively.

DISCUSSION

The present study aimed to examine which variable, between the peak running velocity determined on the track field (V_{peak_TF}) and the critical speed (CS), is the best predictor of the 5-km running performance in recreational runners. The main finding was that CS showed a higher correlation and predictive power for the 5-km running performance, slightly better than that of V_{peak_TF}, which is contrary to the initial hypothesis. Also, the CS values estimated through three TTs (i.e., $CS_{1,2,3}$) and the combination of the shortest and the longest TTs (i.e., $CS_{1,3}$) presented the highest correlation and predictive power for this performance in recreational runners.

This is the first study that demonstrated the relation between both the V_{peak_TF} and CS determined on the track field and the 5-km running performance in recreational runners. These results are in accordance with previous studies that demonstrated a higher correlation and predictive power between the V_{peak_T} and CS determined from a treadmill test protocol performed on the same day and the 5-km running performance in untrained volunteers (Stratton et al., 2009), recreational runners (Machado et al., 2013), and endurance athletes (Nimmerichter et al., 2016). However, it must be emphasized that, unlike the method used in this study, Stratton et al. (2009) determined the V_{peak_T} using a different protocol, not only the duration of the tests but also the initial speed, and the aforementioned studies also conducted both the CS and V_{peak} protocols under laboratory conditions, which could explain the high predictive power for both variables determined on the track field in our study, reflecting the demands of competitive reality and endurance training, as well as the highest ecological validity.

Although the V_{peak_TF} and CS determined on the track field have been shown to be effective predictors of the 5-km running performance, $CS_{1,2,3}$ and $CS_{1,3}$ demonstrated higher correlations and predictive power that were slightly better than those of V_{peak_TF}. This result may be explained by the fact that all values of CS were similar to the MV for the 5-km running performance in the present study (**Table 1**), thus suggesting that the participants may have performed the 5-km running performance at intensities close to 100% of the CS. Previous studies have reported that the t_{lim} at an intensity associated with the CS during running could be sustained for less than 30 min (Pepper et al., 1992; Bull et al., 2008). Interestingly, this is very similar to the average time performed during the 5-km running performance in this study (25.3 ± 3.0 min), confirming that the CS may be held for the length of time taken to complete this performance in recreational runners. However, unlike the CS, previous studies have shown that the t_{lim} at an intensity associated with 100% of the V_{peak} during a treadmill protocol could be sustained for less than 7 min by recreational runners (da Silva et al., 2015; Peserico et al., 2019). Thus, we suggest that the similarity between the CS and the MV for the 5-km running performance may in part explain the higher power of the CS to predict performance.

The present study also showed that the CS estimated through three TTs (i.e., $CS_{1,2,3}$) was not different from the combination of the shortest and the longest TTs (i.e., $CS_{1,3}$) (**Table 1**). These data are in agreement with those of Smith et al. (2011) showing that the CS estimated from the shortest and the longest t_{lim} trials (i.e., 110 and 90% $v\dot{V}O_{2max}$, respectively) can produce similar estimates and the lowest standard error of the mean (SEM) when compared with the CS data from the four t_{lim} trials (i.e., 90, 100, 105, and 110% $v\dot{V}O_{2max}$) on a treadmill in moderately trained runners, respectively. Similarly, Kordi et al. (2019), using a similar method to that proposed in our study, reported that the CS values estimated from the shortest and the longest TTs (i.e., 3,600 and 1,200 m, respectively) were similar and also showed an overall lowest mean bias and SEE in comparison with the CS estimated through three TTs (i.e., 3,600, 2,400, and 1,200 m) in experienced, highly trained runners.

Nonetheless, Maturana et al. (2018) demonstrated that an accurate estimation of critical power (CP) in cyclists was achieved when TTs with longer durations were included when compared with five predictive TTs. However, when only short TTs (i.e., less than 10 min) are used, it might result in a higher or a lower estimation of the CP, leading to poor agreement with the CP estimated from a predetermined criterion method (i.e., five TTs)

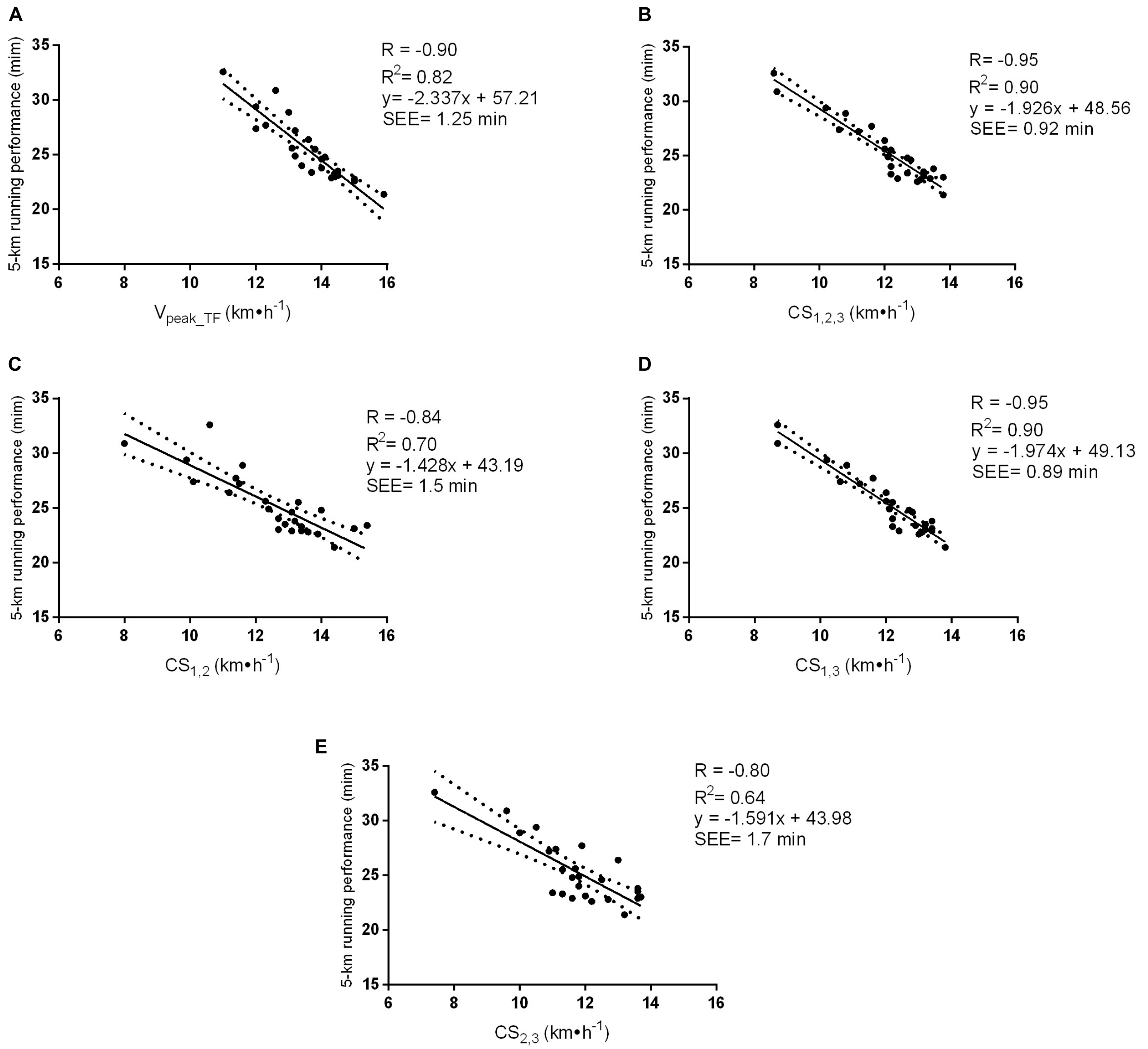

FIGURE 1 | Correlation and linear regression between the (V_{peak_TF}) **(A)**, $CS_{1,2,3}$ **(B)**, $CS_{1,2}$ **(C)**, $CS_{1,3}$ **(D)**, and $CS_{2,3}$ **(E)** with the 5-km running performance time in minutes ($n = 25$). SEE: standard error of the estimate; V_{peak_TF}: Peak running velocity determined on the track field; $CS_{1,2,3}$: Critical speed at 2,600, 1,800 and 1,000 m; $CS_{1,2}$: Critical speed at 2,600 and 1,800 m; $CS_{1,3}$: Critical speed at 2,600 and 1,000 m; $CS_{2,3}$: Critical speed at 1,800 and 1,000 m.

(Maturana et al., 2018). Thus, longer TTs should be included in order to model the CP that more realistically predicts the upper boundary of sustainable endurance exercise, which required a high level of $\dot{V}O_{2max}$ (Morton, 2006). In addition, Bishop et al. (1998) showed that the estimation of CP was higher when the TT durations became shorter, and the opposite was true when the TT durations were lengthened.

Thus, it is necessary that the duration and the number of these distances are carefully selected. Previous studies have recommended the TTs range between 2 and 15 min (Hill, 1993; Bishop et al., 1998), with a minimum of 5 min difference between the shortest and the longest TTs (Housh et al., 1990) to help participants with slower $\dot{V}O_2$ kinetics and also to ensure attainment of the $\dot{V}O_{2max}$ and discharging D' at the end of each exhaustive TT (Simpson and Kordi, 2017). In addition, previous studies have shown that the total number of TTs required to estimate the CS ranges between three and five (Kranenburg and Smith, 1996; Galbraith et al., 2014; Triska et al., 2018), although it is usual for at least three TTs to be performed, especially in non-athletes (Karsten et al., 2014), which is in agreement with the number and the duration range used in the present study.

Although our results suggest that $CS_{1,2,3}$ and the $CS_{1,3}$ accounted for the majority of the total variance associated with predicting the 5-km running performance time when compared to the V_{peak_TF}, this should be carefully interpreted

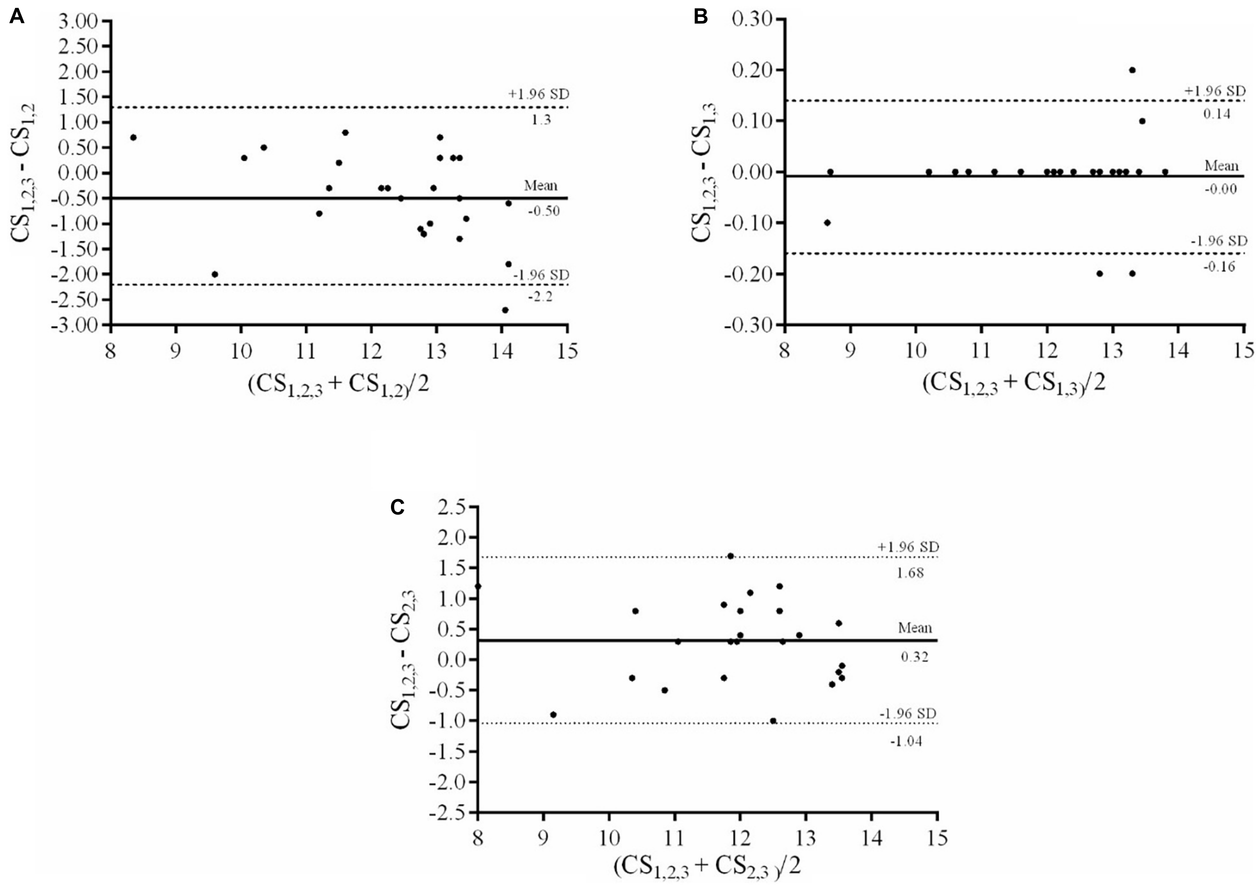

FIGURE 2 | Bland–Altman plots of the differences between $CS_{1,2,3}$ and $CS_{1,2}$ **(A)**, $CS_{1,3}$ **(B)**, and $CS_{2,3}$ **(C)**. *Solid horizontal lines* represent the mean bias, while *dashed lines* represent the lower and upper 95% limits of agreement. $CS_{1,2,3}$: Critical speed at 2,600, 1,800 and 1,000 m; $CS_{1,2}$: Critical speed at 2,600 and 1,800 m; $CS_{1,3}$: Critical speed at 2,600 and 1,000 m; $CS_{2,3}$: Critical speed at 1,800 and 1,000 m.

due to the slight differences in the predictive power found between these variables and the 5-km running performance time (**Figure 1**), with the V_{peak_TF} being almost as good as the $CS_{1,2,3}$ and $CS_{1,3}$. Nevertheless, previous studies have shown that V_{peak_T} is highly reliable (Peserico et al., 2014) and has been reported to be a valid measure to prescribe and evaluate improvements in the endurance performance of recreational runners (Peserico et al., 2019).

In contrast, the lack of reliability on the test for CS that resulted from the different TT combinations in recreational runners can be considered a potential limitation. This may arguably increase the potential use of V_{peak_TF} compared to CS in predicting the 5-km running performance of recreational runners. Thus, further studies are required to examine whether the reliability of the CS that resulted from the different TT combinations has as high reliability as the V_{peak_T} in recreational runners in order to effectively predict endurance performance as well as for the prescription and analysis of the training effects.

Therefore, we conclude that the CS results showed a higher predictive power for the 5-km running performance, slightly better than that of V_{peak_TF}. Also, $CS_{1,2,3}$ and the $CS_{1,3}$ presented the highest predictive power for the 5-km running performance of recreational runners.

PRACTICAL APPLICATION

Understanding the relation between the V_{peak_TF} and CS determined on the track field with the 5-km running performance would enable coaches, practitioners, and endurance runners to increase specificity in the training methods, which will allow improvements of their competitive results. These variables could be considered a more practical way to evaluate and monitor the effects of endurance training, as well as in elucidating a more homogeneous response when used to prescribe adequate exercise intensities compared to other physiological parameters such as the $\dot{V}O_{2max}$, $v\dot{V}O_{2max}$, and LT. We suggest that a well-structured and periodized training program should take these variables into consideration on the track field as a way of improving the 5-km running performance of recreational runners.

Moreover, the proposed equations can be used to predict the 5-km running performance from the results of the V_{peak_TF}, the $CS_{1,2,3}$, and the $CS_{1,3}$ estimated on the track field, which has an easy accessibility for coaches, practitioners, and endurance runners. Finally, the estimation of the CS using the combination of the shortest and the longest TTs (i.e., $CS_{1,3}$) is extremely relevant regarding time efficiency and employing applicability setting (i.e., one training session), which can minimize the time commitment of practitioners and endurance runners during assessments.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Human Research Ethics Committee, State of University of Maringá. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

DioF, DieF, FdAM, and FAM performed material preparation, data collection, and analysis. DioF wrote the first draft of the manuscript. All authors commented on previous versions of the manuscript, read and approved the final version of the manuscript, and contributed to the study conception and design.

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ORIGINAL RESEARCH
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The Effect of a Pace Training Session on Internal Load and Neuromuscular Parameters in Taekwondo Athletes

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This study aimed to verify the effect of a pace training session at an intensity corresponding to the kick frequency at the anaerobic threshold (KF_{AT}) on the internal load response and motor response performance of the roundhouse kick. Twelve black belt taekwondo athletes underwent two evaluation sessions: (1) performed the progressive specific test for taekwondo (PSTT) to identify the heart rate deflection point (HRDP) and the KF_{AT}; (2) performed three 2-min rounds with a 1-min interval. Heart rate (HR) throughout each round and motor response performance before and after sessions were measured. The Student's T-test or Wilcoxon test was used, and $p < 0.05$ was adopted. During round 1, a lower internal load was observed (167 ± 10 bpm) compared with HRDP (179 ± 8 bpm; $p = 0.035$). During rounds 2 (178 ± 10 bpm; $p = 0.745$) and 3 (179 ± 8 bpm; $p = 1$), no differences were observed for an internal load and HRDP. Motor response performance showed no differences. However, a potentiation in the post countermovement jump test compared with rounds 1 ($p = 0.012$) and 2 ($p = 0.028$) was observed. The internal load (HR) observed at the intensity corresponding to KF_{AT} can be considered in the prescription of training when the aim is to control the internal load responses without inducing fatigue.

Keywords: martial arts, heart rate deflection point, physical preparation, mobile technology, anaerobic threshold

INTRODUCTION

Taekwondo is characterized as an intermittent sport, with alternation between attacks involving high-intensity movements and periods of low intensity, or even periods of inactivity (Matsushigue et al., 2009). These characteristics are reflected in an effort: pause ratio (E:P) during combat of from 1:4 to 1:9 (Matsushigue et al., 2009; Santos et al., 2011; Campos et al., 2012; Del Vecchio et al., 2016). During international-level taekwondo competitions, athletes perform 8 ± 3 high-intensity attacks, lasting around 1.3 ± 0.4 s each, combined with 9.2 ± 3.9 s of bouncing movements and 6. ± 3.9 s of referee interruptions, resulting in 1:9 attack to the stepping movement ratio and 1:15 high-intensity actions to the low-intensity and pause ratio (Santos et al., 2011).

Thus, the motor actions in taekwondo that are characteristics of the modality, which imposes the E:P relationship, generate energetic alternations between the moments of aerobic predominance and those determining moments when the anaerobic demand increases (Campos et al., 2012). It is important to note that success in sports such as taekwondo is often associated with rapid motor actions in response to a particular stimulus (Bouhlel et al., 2006; Loturco et al., 2017), such as, for example, the reaction and response times of the kicks (Vieten et al., 2007; Hermann et al., 2008).

In combat sports, the determinant actions that involve anaerobic power (i.e., kick) are supplied by anaerobic energy systems, in particular the anaerobic alactic system (ATP-CP) (Bridge et al., 2009; Obmiński et al., 2011). These actions demand high production of force in small-time intervals, which is known as "the rate of force development" (Lars et al., 2006), and promote increased recruitment of muscle fibers, especially those with rapid contraction (Maffiuletti et al., 2016). Taekwondo athletes must maintain the ability to sustain decisive actions, high anaerobic power, and neuromuscular performance throughout the fight, without compromising the premotor reaction time and response time of the muscles associated with the kick (Sant' Ana et al., 2017).

Therefore, the evaluation of muscle power in combat sports athletes is important. However, although the use of vertical jump tests for this purpose has been questioned (Morin et al., 2019), the countermovement jump test (CMJ) is often used (Loturco et al., 2017). In addition, there is evidence of strong correlations between mean power in the CMJ test and shorter kick cycle times ($r = -0.89$) and mean kick cycle times ($r = -0.79$) in a specific test to assess the power and anaerobic capacity of taekwondo athletes (Sant' Ana et al., 2014). The CMJ test has also been able to discriminate the competitive level of combat sports athletes (Ravie et al., 2004).

Furthermore, the determinant high-intensity actions associated with predominant low-intensity actions, which reflect the external load (i.e., pace or E:P ratio), and consequently generate physiological responses (an internal load) (Kirk et al., 2015), need to be controlled. Some studies show different values of external load (ratio E:P) and internal load responses (e.g., blood lactate and heart rate—HR) in simulated combat situations (Campos et al., 2012), simulated competitions (Bouhlel et al., 2006; Butios and Tasika, 2007), small combat games with each athlete confronting one or two opponents in different area sizes (i.e., 4 × 4 m, 6 × 6 m, and 8 × 8 m) and imposed ratio E:P-—1:2 or free combat (Ouergui et al., 2020, 2021), competitions with a single round (Matsushigue et al., 2009), and official competitions (Bridge et al., 2009; Obmiński et al., 2011). These observational studies, based on means, make it difficult to understand the relationship of external and internal load parameters individually, and the effects of these on neuromuscular performance and determinant actions (kicks) performed by the athlete during combat.

Currently, in taekwondo, the internal load (e.g., HR) has been estimated from external load parameters (e.g., kick frequency—KF) or the pace obtained during progressive specific taekwondo test (PSTT) (Sant' Ana et al., 2019). During these tests, it is possible to obtain an individualized kick frequency at the anaerobic threshold (KF_{AT}) pace or frequency that can be used to modulate the intensity of the training sessions and, also, to verify the effects on specific parameters through the relative intensity of the test (Sant' Ana et al., 2017). However, the literature lacks studies that have verified the effect of using the specific external load (i.e., KF_{AT}), identified in PSTT, on the internal load response, neuromuscular performance, and the specific technique of taekwondo athletes (e.g., kick). Thus, the present study aimed to verify the effect of a pace training session performed at the intensity corresponding to KF_{AT} on the internal load response, performance during the CMJ test, and parameters associated with the neuromuscular and motor performance of the roundhouse kick through the evaluation of premotor reaction time, motor reaction time, and kick response time in taekwondo athletes. Our first hypothesis was that pace training at an intensity corresponding to KF_{AT} would promote internal load responses similar to those observed at the pace intensity determined by the HRDP during the incremental test. Our second hypothesis was that three rounds at a pace-related intensity would cause a drop in CMJ performance and worsen the parameters associated with the motor response time of the roundhouse kick of taekwondo athletes.

MATERIALS AND METHODS

Participants

The sample was an intentional non-probabilistic type composed of a group of 12 male black belt taekwondo athletes (20.7 ± 4. years; 177 ± 6 cm; 73.6 ± 7.9 kg, 12.1 ± 3.5% body fat, and 8.4 ± 5. years of practice). The athletes participating in the study were engaged in at least 1 h of training three times a week. The athletes regularly participated in regional and state competitions, and some of the athletes (three athletes) were national and international level competitors. Considering the Olympic classification of weight division, the participants were referred to as flyweight (one athlete), featherweight (five athletes), welterweight (four athletes), and heavyweight (two athletes).

Study Design

Data collection was carried out in two sessions in the following order: (1) PSTT and (2) training at pace-related intensity. The interval between each session was longer than 48 h. In the first session, the athletes performed the PSTT to identify the HRDP, KF_{AT}, and the intensity related to the training pace through the mobile application *ITStriker* (ETS4ME, São José, SC, Brazil). In the second session, the athletes performed three rounds of 2 min with a 1-min interval, with HR being measured throughout each round, CMJ jump performance and variables associated with premotor reaction time, motor reaction time, and time response of the roundhouse kick pre and post the pace training sessions in the intensity of KF_{AT} (**Figure 1**). The athletes were instructed not to perform any other type of physical effort in the 24 h before data collection. Each individual was informed about the risks and benefits associated with the test protocol. All research procedures were previously approved by the Ethics and Research Committee on Human Beings (protocol No. 145882).

Procedures

Anthropometric Evaluation

To characterize the group of athletes, the following anthropometric variables were measured: height using a stadiometer (Sanny, São Paulo, Brazil), body mass with an electronic scale (Toledo, São Paulo, Brazil), with 0.1-cm and 0.1-kg resolutions, respectively, and thickness of the skin folds was measured, using a scientific compass (Cescorf, Porto Alegre, Brazil), with a 0.1-mm resolution. The percentage of

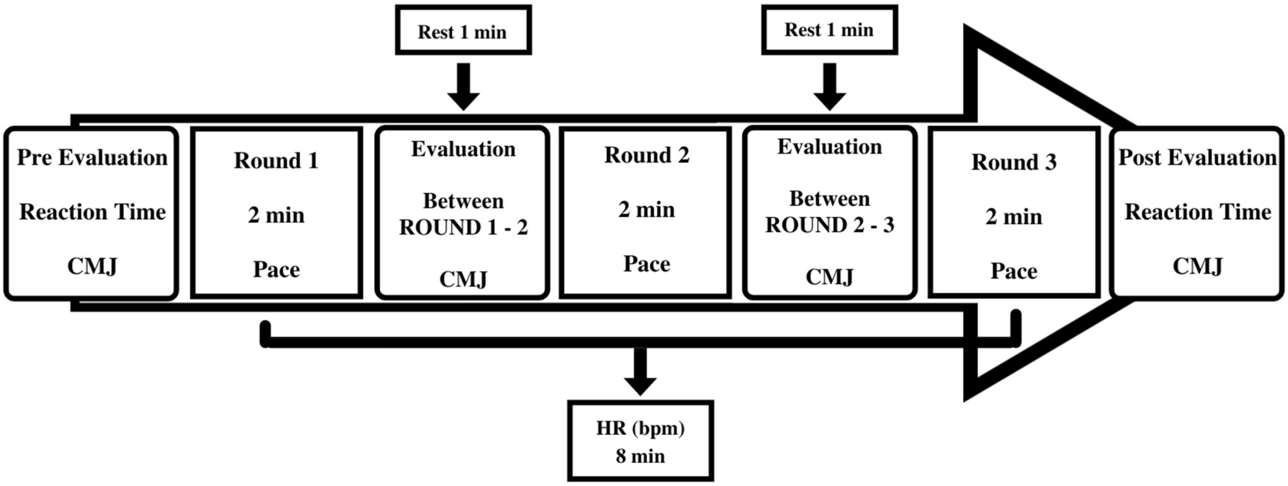

FIGURE 1 | Experimental design of evaluation protocol before, during, and after pace training sessions.

fat was calculated from the Siri equation (Siri, 1961), using the body density established for men (Jackson and Pollock, 1978) obtained through the following skin folds: subscapular, midaxillary, triceps, thigh, supra-iliac, abdomen, and chest. Three measurements were made at each point, all on the right side of the body, and the mean value or value that was repeated two times was recorded. All measurements were performed by a single experienced evaluator.

Progressive Specific Test for Taekwondo Practitioners—PSTT

To perform the PSTT and identify the maximum kick frequency (KF_{MAX}), maximum heart rate (HR_{MAX}), HRDP, KF_{AT}, and training pace by the Dmax method (Kara et al., 1996), the *ITStriker* application and a Bluetooth belt were used to record the HR (Polar H7® Kempele, Finland), paired with the application. The PSTT was performed in an area of 2×2 m demarcated by a mat. A "punching" bag was used for the kicks, which were required to be carried out at a height between the umbilical scar and nipples of the athlete. The subjects began the PSTT with the right leg, and the first stage started with a frequency of six kicks, alternating the legs, with an increase of four kicks at each new stage. During the test, the athletes always kept in step (jumping position) and performed the protocol until exhaustion. For more information about the test, see (Sant' Ana et al., 2019).

Protocol for Pace Training Session

Before trials, the athletes performed a 5-min warm-up, consisting of stretching step movements, knee lifts, and 10 roundhouse kicks performed with each leg. The pace training protocol started 3 min after the warm-up, and the athletes performed three 2-min rounds with a 1-min interval, and HR was measured throughout each round, using a Bluetooth belt paired with the *ITStriker* application. For maintenance of the KF_{AT} and the training pace corresponding to that obtained in the PSTT, the *ITStriker* application was used in the training mode to ensure that the individual pace intensity related to the HRDP of each athlete was maintained throughout all rounds. In addition, to reproduce the technical-tactical actions closer to those carried out in combat, kicks were used with variations in the techniques and combining up to three kicks for each pace, always alternating steps, hoopings, and movements characteristics of taekwondo.

Determination of Premotor Reaction Time, Motor Reaction Time, and Response Time

To determine the premotor reaction time and the response time, synchronization was performed between a light signal and the electromyography (Delsys, Inc., Natick, MA, USA) and kinematics system (Vicon, Oxford Metrics, Oxford, UK). The motor reaction time was determined with kinematics, using reflective markers on the joint of interest. The athletes wore a sock with reflective markers (ankle and lateral malleolus). All the athletes performed three kicks pre and two kicks post the pace protocol, and the best pre and post kicks were used for analysis (**Figure 2**).

To identify the premotor reaction time, defined as the time interval between the visual stimulus and the electromyography activation onset, the activation signal of the rectus femoris muscle generated in each executed kick was identified. As a criterion for determining the premotor reaction time based on muscle activation, using surface electromyography (EMG), the signals were amplified and recorded at a sampling rate of 2,000 Hz, and the raw EMG signals were smoothed with a fourth order Butterworth digital recursive filter (20–500 Hz). Baseline EMG activity was assessed 150 ms before each light signal used to determine the kick execution. An increase in the EMG signal equal to five times the standard deviation of this reference value was used to determine the premotor reaction time (Hopper et al., 1998).

Response time was defined as the total time between the presentation of the visual stimulus until the moment when the blow hit the target (punch ball) marked with reflective markers

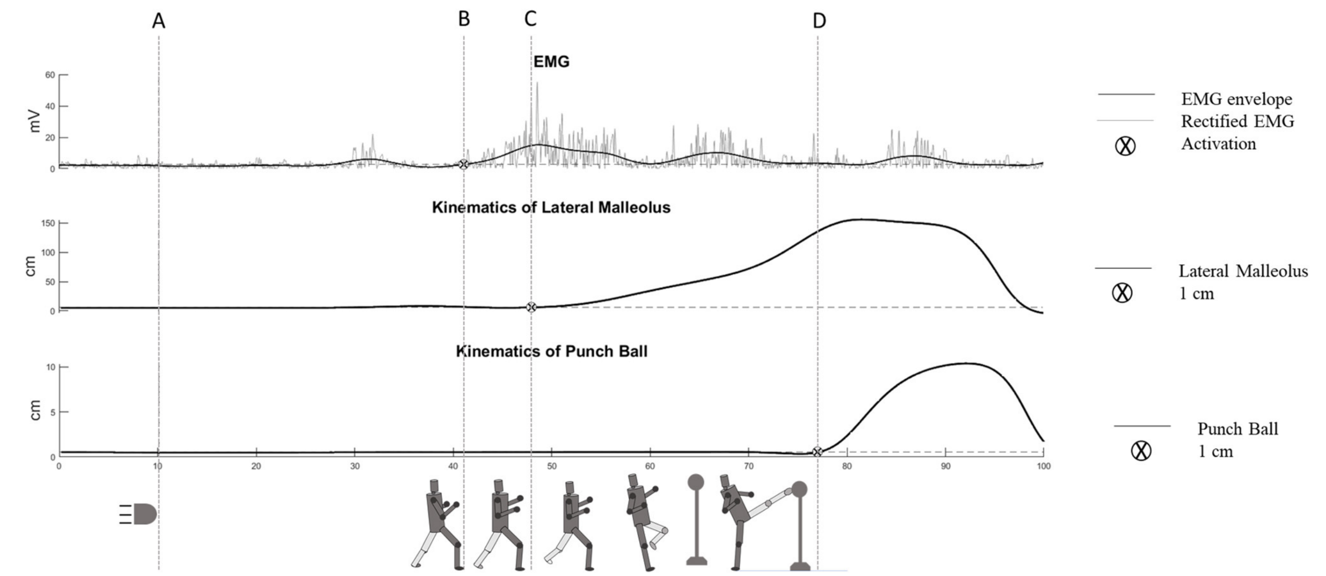

FIGURE 2 | Measurement of the parameters associated with the neuromuscular and motor performance of the roundhouse kick from a representative participant. The dot line **(A)** represents the visual stimulus; **(B)** represents the electromyography activation onset of the rectus femoris muscle; **(C)** represents the kinematics of the lateral malleolus onset (movement of 1 cm of the lateral malleolus marker), and **(D)** represents the target onset (movement of 1 cm of the punch ball marker).

and showing a movement of 1 cm. Both response times and motor reaction times were measured, using the motion analysis system with a sampling frequency of 400 Hz. The technique used was the semicircular kick performed at the height of the head of the athlete, and the distance from the target was standardized, ensuring that the support foot, in the pre- and post-pace training moments, was placed in the same position demarcated on the floor.

Determination of Movement Time, Time of Performance, and Electromechanical Delay

The movement time was determined as the time interval between the response time and the kinematic motor reaction time, the performance time as the time interval between the premotor reaction time and the response time, and the electromechanical delay as the difference between the premotor reaction time and the kinematic response time.

Vertical Jump Test

Vertical jump performance was evaluated, using the CMJ test. All the athletes were familiar with the type of jump. The protocol consisted of three attempts, performed pre and post the pace training protocol and at each interval of the 2-min rounds. The test consists of adopting a standing position with the hands on the hips, bending the knees close to 90°, and performing a maximum jump. Performance (i.e., jump height) was measured, using a piezoelectric force platform (Kistler, Quattro jump, 9290AD, Winterthur, Switzerland), with a sampling frequency of 500 Hz. Three attempts were allowed, and the best jump was considered for the analysis. For the analysis of the height of the jump, the software of the force platform (Kistler, Quattro jump, 9290AD, Winterthur, Switzerland) was used.

Statistical Analysis

Descriptive statistics (mean and standard deviation) were used to present the data. Normality was verified, using the *Shapiro–Wilk* test and homogeneity by the Levene test. ANOVA with repeated measures followed by the Tukey's test was used to compare the HRDP and HR of rounds 1, 2, and 3, as well as performance in the CMJ, and the *t*-test or Wilcoxon test for dependent samples was used to compare the motor variables of the roundhouse kick pre- and post-pace training. The magnitude of the differences was verified, using the effect size according to (*d*) (Cohen, 1969) or (*r*) (Pallant, 2007) and classified as trivial (<0.25), small (0.25–0.50), moderate (>0.50–1.0), or large effects (>1.0) (Rhea, 2004). A significance level of $p < 0.05$ was adopted. For the analysis and treatment of the data, Microsoft Office Excel 2007, Matlab 7.1 (MathWorks, Natick, MA, USA), and SPSS 17.0 software (SPSS Inc., Chicago, IL, USA) were used.

RESULTS

Table 1 presents the mean and standard deviation of the variables of the specific taekwondo test in taekwondo athletes.

Table 2 shows the internal load responses with the HR values obtained in the PSTT and during the three rounds of pace training performed at the intensity corresponding to KF_{AT}. During round 1, a lower internal load value was observed compared with HRDP ($p = 0.0001$). No differences were observed concerning an internal load and HRDP to rounds 2 ($p = 0.456$) and 3 ($p = 1$). The difference verified, using the effect size, presented a large effect ($d = 1.360$), comparing HRDP and HR during round 1. During rounds 2 and 3, the differences verified,

TABLE 1 | Mean and standard deviation of the variables obtained during the progressive specific taekwondo test (PSTT) ($n = 12$).

KF_{MAX}	KF_{AT} (pace)	HR_{MAX}	HRDP
33 ± 4 kicks	18 ± 2 kicks	195 ± 7 bpm	179 ± 8 bpm

KF_{MAX}, maximal kick frequency; KF_{AT}, anaerobic threshold kick frequency; HR_{MAX}, heart rate maximal; HRDP, heart rate deflection point.

TABLE 2 | Mean and standard deviation of the variables obtained during the pace training at an intensity corresponding to the intensity of the heart rate deflection point (HRDP) ($n = 12$).

HRDP (CI)	HR_{ROUND1} (CI)	HR_{ROUND2} (CI)	HR_{ROUND3} (CI)
179 ± 8 bpm (174 – 185)	167 ± 10 bpm[a] (160 – 173)	178 ± 11 bpm[b] (171 – 184)	179 ± 10 bpm[b] (173 – 186)

HR, heart rate; internal load value for rounds 1, 2, and 3 in comparison with the HRDP obtained for the pace identified during the PSTT.
[a]Different to HRDP.
[b]Different to round 1.
CI, confidence interval.

using the effect size, presented trivial effect, comparing HRDP and HR ($d = 0.167$ and $d = 0$, respectively).

Table 3 shows the performance in the CMJ. No difference in mean values pre- and post-pace training was observed ($p = 0.227$). The difference in the performance of CMJ post compared with the values was observed for performance in the intervals of rounds 1 ($p = 0.011$) and 2 ($p = 0.028$). However, a small effect size was observed compared with pre and post CMJ ($d = 0.264$) and performance post compared with values in the intervals of rounds 1 ($d = 0.422$) and 2 ($d = 0.388$).

Table 4 presents the mean and standard deviation of the parameters associated with the neuromuscular and motor performance of the roundhouse kick during the evaluation pre and post the training of pace rounds in taekwondo athletes. No differences ($p > 0.05$) were observed between the moments pre- and post-pace training for CMJ and any of the variables associated with the reaction performance and motor response of the roundhouse kick, but a significant increase in the height of the vertical jump was observed in the CMJ test post-training in relation to the jumps recorded in the intervals between rounds. The differences verified using the effect size presented trivial and small magnitude effect.

DISCUSSION

The present study aimed to verify the effects of a pace training session at an intensity corresponding to KF_{AT} on the internal load response (HR), performance of the CMJ test, and parameters associated with the premotor reaction time, motor reaction time, and motor response of roundhouse kicks in taekwondo athletes. The observed results confirmed the hypothesis formulated for the present study, in which we suggest that the internal load (HR) observed during a pace training session would be similar to the intensity corresponding to that observed for pace intensity identified during a specific taekwondo test. On the other hand, the hypothesis that pace training would cause a reduction in the performance of the variables associated with neuromuscular performance and CMJ, as well as in the roundhouse kick reaction and response time variables in taekwondo athletes, was rejected.

In taekwondo, when planning a training program, it is necessary to consider the specific demands of the sport and its intermittent characteristics (Matsushigue et al., 2009; Campos et al., 2012; Del Vecchio et al., 2016). It is also necessary to take into account the principle of individuality, from the parameters of specific tests, such as the one used in the current study (PSTT) to help identify the internal load responses and prepare a more assertive intervention, using the individual pace in order to obtain greater control of the specific E:P ratio of the athlete and the expected adaptations from the intervention.

In the present study, the anaerobic threshold pace of the athletes, characterized by the KF_{AT}, and with a mean E:P ratio of ∼1:4, generated internal load (HR) responses (167, 178, and 179 bpm, for the rounds 1, 2, and 3, respectively). Only in the first round was observed an internal load value lower than that of the HRDP determined during the PSTT ($p = 0.035$). In addition, it was not possible to verify a negative influence ($p > 0.05$) of the pace intensity (**Table 2**) on the parameters associated with the neuromuscular and motor performance of the roundhouse kick in taekwondo athletes.

The movement time, both pre and post, observed in the present study presented better performance (shorter times) in relation to the athletes of the Spanish team and with higher values and worse performances in relation to the athletes of the German team (Hermann et al., 2008; Falco et al., 2011). The pre-pace training response time values observed in the present study were higher than those observed in a previous study, while the post-pace training values were lower (Sant' Ana et al., 2017). When comparing the response time values with the values (646 ms) observed in the athletes of the German team (Hermann et al., 2008), the athletes in this study presented higher values, and the values after the pace protocol were similar to the values (740 ms) observed in athletes from the Spanish team (Falco et al., 2011). Several factors may have influenced the values and differences observed between the present study and those mentioned above: (1) the intensity applied during the pace protocol, (2) the level of the athletes, and (3) the height of the kicking target. In the present study, the target was positioned at the height of the head of the athlete, while, in the study by Sant' Ana et al. (2017), the target was placed at the height of the trunk, in the study

TABLE 3 | Mean and standard deviation of the performance in the countermovement jump test (CMJ) pre, post, and in the interval of the rounds of pace training performed at the intensity corresponding to the kick frequency at the anaerobic threshold ($n = 12$).

CMJ_{PRE} (CI)	CMJ_{REST1} (CI)	CMJ_{REST2} (CI)	CMJ_{POS} (CI)
46.4 ± 5.33 cm (42.9 – 50.0)	45.4 ± 6.01 cm (41.4 – 49.4)	45.7 ± 5.67 cm (41.9 – 49.4)	47.9 ± 5.71 cm* (44.1 – 51.7)

*CMJ_{PRE}, value for CMJ pre-pace training; CMJ_{REST1}, value for CMJ during rest between rounds 1 and 2; CMJ_{REST2}, value for CMJ during rest between rounds 2 and 3; CMJ_{POS}, value for CMJ post-pace training. *, difference between rests 1 and 2 to post; CI, confidence interval.*

TABLE 4 | Mean and standard deviation and the effect size (ES) of the parameters associated with the neuromuscular and motor performance of the roundhouse kick during the evaluation pre and post the training of pace rounds in taekwondo athletes ($n = 12$).

	Pre	Post	(CI)	*P*	*d* (ES)	*r* (ES)
Premotor reaction time (ms)	311 ± 153	295 ± 76	(214 – 409)	0.548	−0.141	–
Response time (ms)	843 ± 235	743 ± 103	(677 – 999)	0.272	–	0.037
Motor reaction time kinematic (ms)	420 ± 147	404 ± 88	(327 – 514)	0.570	−0.139	–
Movement time (ms)	423 ± 231	339 ± 98	(276 – 569)	0.195	–	0.040
Electromechanical delay (ms)	109 ± 50	109 ± 51	(77 – 142)	0.993	−0.002	–
Performance time (ms)	532 ± 258	448 ± 96	(368 – 696)	0.239	–	0.056
Performance CMJ (cm)	46.4 ± 5.3	47.9 ± 5.7	(42.9 – 51.7)	0.130	0.260	–

CMJ, countermovement jump test.

with athletes of the German team (Hermann et al., 2008) at the height of the waist, and the study with athletes of the Spain team (Falco et al., 2011) at the height of the trunk. Additionally, the measurement instruments used to determine the variables may have influenced the observed differences. In the studies by Hermann et al. (2008) and Falco et al. (2011), the variables time of movement and response time were determined by means of kinematics, like in the present study; however, the sampling frequency used to record the movement of the kick in both studies (150 and 300 Hz, respectively) differs from that used in the present study (400 Hz). In the study by Sant' Ana et al. (2017), the authors determined the response time, using accelerometers, making comparisons difficult.

The premotor reaction time values of the present study, both pre- and post-pace protocol, are higher than those observed in a previous study with seven taekwondo athletes (Sant' Ana et al., 2017). On the other hand, when observing the effect of pace training on the intensity, corresponding to the maximum oxygen consumption in taekwondo athletes, worsening of the premotor reaction time of the athletes was observed, as well as a decrease in the impact of the roundhouse kick (Sant' Ana et al., 2017). Associated with this, the fact that no changes in the electromechanical delay were observed allows us to infer that the pace protocol at the intensity corresponding to KF_{AT} did not compromise the neuromuscular performance of the roundhouse kick and did not generate fatigue in the athletes. It should be noted that the electromechanical delay can be influenced in situations of fatigue, being responsive to processes, such as propagation of the action potential; an excitation-contraction coupling process; triggering system of gamma motor neurons; and the recruitment of muscle fibers, factors that influence the time between the start of muscle activation and limb acceleration (Norman and Komi, 1979).

Another important finding of the present study that reinforces that the intensity of the KF_{AT} does not seem to compromise the performance and/or generate fatigue in the athletes is the fact that this intensity generated a potentiation effect in the performance of the CMJ (**Table 3**). After the three rounds of the pace protocol, there was a 3.1% improvement in the performance of the CMJ compared with pre, and a significant improvement of 5.4 and 4.8% compared with the CMJ post rounds 1 and 2, respectively. A case study with a World Karate Champion athlete (Loturco et al., 2017) also observed the improvement effect (2.9%) in the performance of the CMJ test pre and post a simulated fight. The authors of this study suggest that, in karate, there is little demand for kicking and lower limb techniques, as reported by Chaabene et al. (2014), and, as a consequence, a post-activation potentiation effect in CMJ was observed.

However, this fact goes against the findings of the present study, in which the kick technique was required throughout the pace training, and we also observed a post-activation potentiation effect on the jumping performance. Therefore, our findings demonstrate that the post-activation potentiation in the performance of the jump after simulated rounds and or fights may be associated with the intensity and economy capacity of the athlete according to the demand. As observed in the present study, when the athlete performs motor actions at a relative pace that does not overlap the KF_{AT}, this should not impair the performance of the specific kick technique in any of the components associated with the reaction and response time of the kick. The post-activation potentiation observed in the CMJ may also be the result of aspects of the mechanics and kinetics involved in the CMJ jump performance test. The jump is a motor gesture distinct from those performed by combat sports athletes. In the execution of the roundhouse kick, there is flexion in the hip joint and extension of the knee joint, while, in the jump, there is a hip extension and knee extension. Thus, some of the mechanisms suggested by Baker (2003), such as increased recruitment of motor units, improved synchrony of the firing of nerve impulses, and, mainly, the reduction of the influence of central inhibitory mechanisms (Renshaw cells) and peripherals (Golgi tendon organ) and increased reciprocal inhibition of the antagonistic musculature could better explain the post-activation potentiation effect observed in CMJ, after a simulated fight or pace training.

Thus, the results of the present study demonstrate that the incremental evaluation in taekwondo athletes can be an alternative tool to establish the individualized E:P ratio. HR can be used as an internal load marker and, through HRDP and KF_{AT}, can be used as an external load indicator associated with the anaerobic threshold, as well as to establish the individual pace (E:P) in dynamics with motor actions close to those performed by athletes in combat to propose pace training rounds, to generate expected physiological responses, and to obtain greater control of the intensity and organic adaptations that are desired individually for each athlete. Additionally, no difference was found between the HRDP identified in an incremental test on a treadmill and the PSTT (Sant' Ana et al., 2019). Just as there was no difference between the anaerobic threshold determined in a rectangular load protocol, by means of fixed concentrations of 4 $mmol \cdot L^{-1}$ (Heck et al., 1985), compared with the anaerobic threshold determined by the HRDP when applying the PSTT (Sant' Ana et al., 2009). All of these findings point to the possibility of this variable being used to control the internal load of athletes and the marker of internal response for a given external load applied.

Finally, as in taekwondo, there is predominance of aerobic demand brought by determinant actions of high intensity, which make demands on the alactic anaerobic system (Campos et al., 2012), and which denote the modality; this characteristic is imposed by the relationship of high and low-intensity activities. Considering the KF_{AT}, estimated by the HRDP, it may be a possibility for the training of athletes of the modality, mainly when greater control and precision are required in relation to the internal load that it is intended to impose on the athlete. In addition, the use of pace training protocols enables the development of specific skills (kicking techniques), including the determinant anaerobic components, since high-intensity kicks, characteristic of the intermittent mode, are present throughout the incremental protocol and during the pace training protocols.

This study had some major limitations that should be considered while interpreting our findings. The first one is the small sample size and the level of the athletes assessed. Thus, future studies should include a larger number of athletes with different competitive levels. In addition, only the intensity corresponding to the HRDP was evaluated. Thus, future studies should compare different relative paces above and below the HRDP. Lastly, they may include other internal load variables, such as oxygen uptake and blood lactate concentration, are necessary to better understand the effects of pace on internal load and neuromuscular parameters and about kick response time in taekwondo athletes. Furthermore, it is important to emphasize the aspects related to the nature of the incremental test (i.e., PSTT) and pace protocols with the intrinsic characteristics of combat sports. Among these aspects is the inability to maintain and reproduce a similar intensity, speed, and strength of the kicks during the test. Therefore, future studies with the use of electronic vests may be an alternative to ensure that the minimum required intensity is reached during the execution of the kicks.

PRACTICAL APPLICATIONS

The pace training, using the KF_{AT} parameter estimated by the HRDP, is a simple methodology to execute, presents low cost, and provides relevant sport-specific information. Outcomes from this study type appoint to practical applications of the methodology with a great advantage for coaches and athletes to not only evaluate performance and determine the optimal workload but also to organize and monitor taekwondo training programs, especially those focused on improving the aerobic component of the sport. The protocol proposed in the present study allows obtaining relevant and specific information on aerobic capacity and power (i.e., maximal kick frequency, KF_{AT}, and pace) simpler and cheaper for coaches and athletes. Finally, we believe that our findings are important to encourage coaches and trainers to raise training loads monitoring and a prescription with greater control and precision in relation to the internal load that it is intended to impose on the athlete.

CONCLUSIONS

The internal load (HR) during rounds of pace training performed at the intensity corresponding to KF_{AT} is equivalent to the anaerobic threshold (HRDP) and can be considered in the prescription of training when the aim is to control the internal load responses without inducing fatigue since no impairment in neuromuscular performance was observed in the performance of the CMJ and the roundhouse kick technique.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical approval was obtained from the local Human Research Ethics Committee of the Federal University of Santa Catarina (protocol number 145882). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JS and RS carried out the data collection. JS carried out all the statistical analyses. All authors conceived the study design, participated in the interpretation of data, drafted the manuscript, and read and approved the final version of the manuscript.

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Runners Employ Different Strategies to Cope With Increased Speeds Based on Their Initial Strike Patterns

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In this paper we examined how runners with different initial foot strike pattern (FSP) develop their pattern over increasing speeds. The foot strike index (FSI) of 47 runners [66% initially rearfoot strikers (RFS)] was measured in six speeds (2.5–5.0 ms^{-1}), with the hypotheses that the FSI would increase (i.e., move toward the fore of the foot) in RFS strikers, but remain similar in mid- or forefoot strikers (MFS) runners. The majority of runners (77%) maintained their original FSP by increasing speed. However, we detected a significant (16.8%) decrease in the FSI in the MFS group as a function of running speed, showing changes in the running strategy, despite the absence of a shift from one FSP to another. Further, while both groups showed a decrease in contact times, we found a group by speed interaction ($p < 0.001$) and specifically that this decrease was lower in the MFS group with increasing running speeds. This could have implications in the metabolic energy consumption for MFS-runners, typically measured at low speeds for the assessment of running economy.

Keywords: strike index, human locomotion, running economy (RE), velocity, running strategy, foot strike patterns

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INTRODUCTION

Foot strike patterns (FSP) describe the location of the first contact area of the foot with the ground (Cavanagh and Lafortune, 1980) during running. At comfortable speeds, runners most commonly strike with the rear part of the foot (∼78%), while the rest strike with the middle or the front part of the foot (Santuz et al., 2016). The two strategies provide very distinct running patterns, exhibiting differences in a plethora of biomechanical characteristics (Hayes and Caplan, 2012; de Almeida et al., 2014; Almeida et al., 2015; Strauts et al., 2015; Valenzuela et al., 2015). For instance, it is well accepted that runners that strike the ground with the heel exhibit a lower peak vertical ground reaction force, lower external dorsiflexion moment and range of motion, while having a higher loading rate of the vertical ground reaction forces and knee extension moment in comparison to runners with a more anterior point of force application (Almeida et al., 2015; Valenzuela et al., 2015). Moreover, certain FSPs have been linked to different injuries (Cheung and Davis, 2011; Daoud et al., 2012; Rice et al., 2013) and to affect performance (Di Michele and Merni, 2014; Ogueta-Alday et al., 2014; Ekizos et al., 2018).

The common strategy employed by humans to increase speed until ∼7 ms^{-1} is by exerting larger vertical ground reaction forces (Arampatzis et al., 1999; Weyand et al., 2000), which leads to increments in step length (Mercer et al., 2002; Dorn et al., 2012). Ground reaction forces subsequently increase the loading on the human system and have to be produced in shorter contact times that are associated with increasing velocities (Gatesy and Biewener, 1991; Arampatzis et al., 2000). Except the overall higher loading, the transition from a lower to a higher speed taxes the human system with an increased oxygen consumption. However, humans maintain similar energy costs (J/kg per meter distance) in a range of running speeds (Margaria et al., 1963; Carrier et al., 1984; Bramble and Lieberman, 2004). From a mechanical point of view, it has been suggested that these increases in running speed are achieved through a repositioning of the foot in relation to the ground. It is suggested that runners gradually adapt their FSP in order to modify the impact of loading or energy costs (Cheung and Davis, 2011; Cheung and Rainbow, 2014; Di Michele and Merni, 2014) and gradually employ a more anterior point of force application at first contact (Keller et al., 1996). However, previous reports did not find a consistent behavior regarding the changes of FSP with increasing speeds. Some studies report that the point of force application moves to the anterior with increasing speeds (Keller et al., 1996; Wang et al., 2018), but this alteration was not confirmed by other studies (Breine et al., 2014, 2019; Cheung et al., 2017). Furthermore, Forrester and Townend (2015), using the foot strike angle (i.e., angle of the foot with respect to the ground in the sagittal plane) as assessment parameter to classify FSP, found that the most runners did not change their initial foot strike angle by increasing running speeds. However, they identified also a cluster of rearfoot strike (RFS) runners that showed a decrease in foot strike angle indicating a trend to midfoot strike (MFS) patterns at higher speeds (Forrester and Townend, 2015). It seems, therefore, that runners are using diverse strategies concerning the FSP behavior to cope with increasing speeds.

Until now, there is no established consensus regarding the changes in FSP with increasing speeds. FSP is a discrete rather than a continuous variable (Breine et al., 2014) and thus changes within a given strike pattern may not be considered examining only the possible transfer from RFS to MFS and vice versa. Thus, a numerical continuous parameter like the foot strike index (FSI), may be a more appropriate way to investigate the modulation of FSP in different running speed conditions (Breine et al., 2014; Santuz et al., 2016). At speeds, which can be sustained for longer periods of time, the human system is more comfortable to exhibit its preferential or more familiar FSP. When increasing speed, the system is forced to accommodate the higher loads and alterations in FSI may be associated with the runners FSP at the comfortable speed. Non-rearfoot strikers, for instance, have a lower margin to increase their FSI anteriorly compared to rearfoot runners. Consequently, runners with a non-rearfoot strike pattern may retain a similar FSI throughout increasing running speeds. It is therefore possible, that the strategies of rearfoot and non-rearfoot strike runners could develop differently as speed progresses and particularly an alteration of FSI toward anterior only in rearfoot runners could be expected. In the current study, we examined the effect of speed on the FSI separately for runners with a rear and non-rear foot strike pattern. We hypothesized (1) a change of FSI in runners with a rear strike pattern toward the fore of the foot, leading to a higher percentage of non-rear foot runners by increasing running speed and (2) runners with an initial non-rear strike pattern would maintain the same strike pattern strategy.

METHODS

Experimental Design

In the current study 47 young adults who were recreational runners (37 males and 10 females, training sessions per week: 3.7 ± 1.6, training duration per week 5.1 ± 2.8 h) have been recruited (age: 27.8 ± 4.8 years, height: 177.3 ± 8.6 cm, mass 70.9 ± 9.2 kg). For each participant the measurement took place on a single day. None of the participants had any neuromuscular or musculoskeletal impairments at the time of the measurements. Moreover, in the 6 months prior to the day of the measurements, none of them have suffered any injury to the lower limbs. All participants gave informed consent and approval of ethics has been acquired from the appropriate committee of the Humboldt-Universität zu Berlin (HU-KSBF-EK_2018_0013).

For the measurements we used a treadmill (mercury, H-p-cosmos Sports & Medical GmbH, Nussdorf, Germany) with an integrated pressure plate operating at 120 Hz (FDM-THM-S, zebris Medical GmbH, Isny im Allgäu, Germany). After a self-selected warm-up, the participants ran shod at six predefined sub-maximal fixed velocities; 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 ms^{-1}. The chosen speeds were comfortably attainable by all participants for small periods of time. While in non-homogeneous groups relative intensity can provide methodological advantages, the homogeneity presented in our cohort meant we could use fixed speeds. As such, possible differences in the relative intensity would not skew our results and comparability with other studies is increased. The duration of the run at each speed was 2 minutes, of which the first minute was used as familiarization to the specific speed and the latter minute was extracted for subsequent analysis.

To calculate the contact time of each step we used the pressure plate data from the treadmill. The time that each foot was in contact with the ground has been calculated based on the time difference, between the first non-zero data after the swing phase and the first zero in the pressure data right after toe-off. We used the average of all contact times of both feet in all steps per trial per person for the statistical analysis. Cadence was calculated from the number of steps detected over the whole trial period. Subsequently, step length, step time and flight time were calculated based on these values. The duty factor was calculated as the ratio of contact time over step time.

The FSP was numerically quantified using the pressure distributions from the instrumented treadmill, through the strike index. The FSI is defined as the distance from the heel to the center of pressure at first impact, relative to the total foot length and was calculated based on the recorded foot pressure distribution using a validated custom algorithm (Santuz et al., 2016). In short, after physically measuring the shoe length (to account for incomplete footstrikes), the algorithm compares it to the calculated length (i.e., using the pressure plate data) and corrects the footstrikes when necessary (Santuz et al., 2016). The first recorded data (i.e., initial contact) at touchdown of each foot in every step are then localized to the full length of the foot. The values, therefore, range from the most posterior part of the heel representing 0 up to the most anterior part of the toes representing 1 (non-dimensional). In our paper we aimed at showing the behavior of the system as a whole and thus we used the average of the strike indexes of both feet in all steps per trial per person. The symmetry in the FSI between left and right foot was quite high depicting an association of $R^2 = 0.887$ and differences were not statistically significant ($p > 0.05$) in all investigated speeds.

Generally, footstrikes are divided in three distinct categories based on where the first impact is located, in relation to the whole foot. A RFS is considered one that provides a strike index lower than 0.33 and thus first touch occurs at the heel of the foot, a midfoot strike one that provides values between 0.33 and up to 0.66 (approximate point of the metatarsophalangeal joints), and a forefoot strike one with values above 0.66 (Cavanagh and Lafortune, 1980; Hasegawa et al., 2007). Due to forefoot strikers exhibiting a low prevalence in the general population (Hasegawa et al., 2007; Larson et al., 2011; Santuz et al., 2016), in this study the participants exhibiting a mid- or a forefoot strike have been grouped together as MFS for all further analysis.

Statistics

We defined two groups based on the FSI at the slowest running speed (i.e., 2.5 ms^{-1}). In that way a RFS (n = 31) and a MFS group (n = 16) have been identified. To further examine the differences and development of FSI, contact time, cadence, step length, step time, flight time and duty factor with speed based on the identified groups, we performed a two-way repeated measures ANOVA. Speed was selected as a 6-level within-subject factor and groups (RFS, MFS) as the between-subject factor. The level of significance was set to $\alpha = 0.05$.

RESULTS

Investigating the effect of running speed for the FSI we found an interaction between the two groups [$F_{(2,5)} = 5.2$, $p = 0.005$; **Figure 1**]. The *post hoc* analysis by means of a repeated measures ANOVA revealed a significant decrease in the FSI in the MFS group [$F_{(2,5)} = 4.3$, $p = 0.018$] and no significant differences in the RFS group [$F_{(1,5)} = 2.5$, $p = 0.104$].

Contact times decreased significantly with increasing velocities [$F_{(2,5)} = 799.8$, $p < 0.001$] in both RFS and MFS groups, while between groups there was a significant effect [$F_{(1,5)} = 8870$, $p < 0.001$] with a clearly higher contact time in the RFS group (**Figure 2**). We found a group by speed interaction [$F_{(2,5)} = 10.4$, $p < 0.001$] in the contact time. In the *post hoc* analysis, both groups exhibited significantly decreased contact times with increasing velocities [RFS: $F_{(1,5)} = 718.4$, $p < 0.001$; MFS: $F_{(1,5)} = 244.9$, $p < 0.001$], therefore the interaction indicate a higher decrease of contact time in the RFS group.

Cadence increased with increasing speeds [$F_{(2,5)} = 309$, $p < 0.001$] and showed no interaction effects [$F_{(2,5)} = 1.8$, $p = 0.180$; **Table 1**]. Similarly, there was an increase [$F_{(2,5)} = 2132$, $p < 0.001$] and no interaction in the development of step length [$F_{(2,5)} = 1.7$, $p = 0.197$]. Step time decreased [$F_{(2,5)} = 313$, $p < 0.001$] as a function of running speed without any interaction effects [$F_{(2,5)} = 1.9$, $p = 0.155$]. Flight times increased significantly with increasing velocities [$F_{(2,5)} = 138$, $p < 0.001$] and showed a significant interaction between groups and speed [$F_{(2,5)} = 4.2$, $p = 0.024$]. *Post hoc* comparisons evidenced a statistically significant [$F_{(2,5)} = 370$, $p < 0.001$] lower flight time in RFS runners in all speeds (**Table 1**). Duty factor decreased significantly with increasing speeds and an interaction was also observed between speed and group [$F_{(2,5)} = 4.9$, $p = 0.016$].

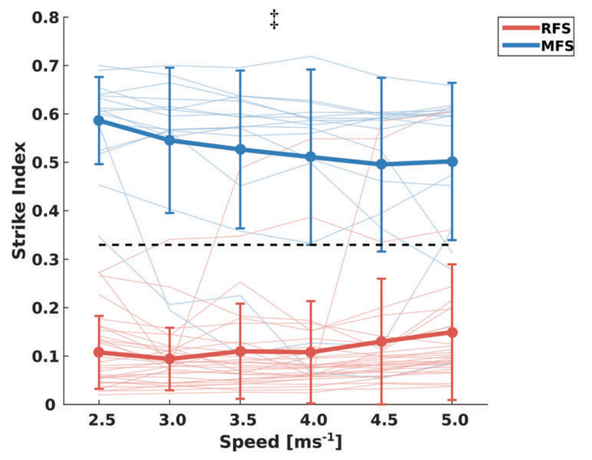

FIGURE 1 | Mean ± standard deviation of the strike indexes throughout the examined speeds and the individual values for both rearfoot strikers (RFS) and mid-forefoot strikers (MFS). The black dotted line indicates the separation between RFS (below 0.33 of strike index) and MFS (above 0.33 of strike index). ‡: statistically significant group × speed interaction ($p < 0.05$) indicating a decrease of strike index only in MFS group.

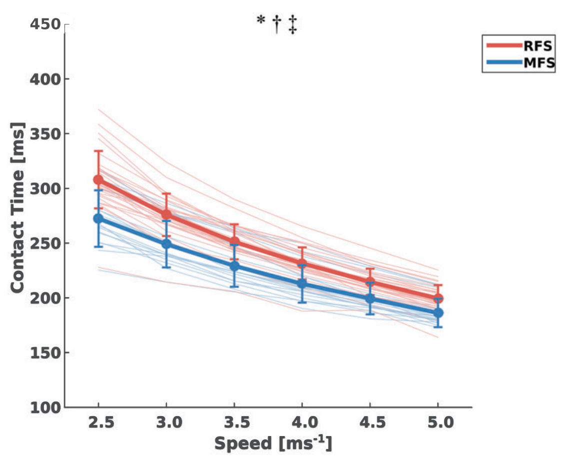

FIGURE 2 | Mean ± standard deviation of contact times [ms] throughout the examined speeds and the individual values for both rearfoot strikers (RFS) and mid-forefoot strikers (MFS). *: statistically significant speed effect ($p < 0.05$); †: statistically significant group effect ($p < 0.05$); ‡: statistically significant group x speed interaction ($p < 0.05$) indicating a greater decrease of contact time in RFS group.

TABLE 1 | Mean± standard deviation of the cadence, step length, step time, flight time, and duty factor for the rearfoot strikers (n = 31) and mid-forefoot strikers (n = 16).

Speed [ms^{-1}]	Cadence [steps/min]*			Step length [m]*			Step time [ms]*			Flight time [ms]*†‡			Duty Factor [%]*†‡		
	RFS	MFS	p	RFS	MFS	p	RFS	MFS	p	RFS	MFS	p	RFS	MFS	p
2.5	162 ± 9	164 ± 11	0.965	0.93 ± 0.05	0.92 ± 0.06	0.977	371 ± 21	368 ± 24	0.977	63 ± 30	96 ± 32	0.004	83.1 ± 7.5	74.2 ± 7.9	0.001
3.0	168 ± 11	168 ± 11	0.965	1.07 ± 0.07	1.07 ± 0.07	0.977	358 ± 24	358 ± 24	0.977	82 ± 25	109 ± 26	0.004	77.2 ± 5.9	69.8 ± 6.4	0.001
3.5	173 ± 12	174 ± 12	0.965	1.22 ± 0.08	1.22 ± 0.08	0.977	348 ± 24	347 ± 24	0.977	96 ± 23	118 ± 25	0.007	72.5 ± 5.3	66.2 ± 5.9	0.001
4.0	180 ± 12	180 ± 14	0.965	1.34 ± 0.10	1.34 ± 0.10	0.977	335 ± 24	335 ± 26	0.977	104 ± 22	122 ± 26	0.012	69.3 ± 4.9	63.8 ± 5.7	0.001
4.5	186 ± 12	184 ± 14	0.965	1.46 ± 0.10	1.48 ± 0.11	0.977	325 ± 22	329 ± 24	0.977	110 ± 20	129 ± 24	0.007	66.3 ± 4.3	60.9 ± 5.3	0.001
5.0	193 ± 13	190 ± 15	0.965	1.56 ± 0.11	1.59 ± 0.12	0.977	313 ± 22	318 ± 24	0.977	113 ± 19	132 ± 24	0.007	64.0 ± 4.2	58.8 ± 5.1	0.001

Between groups comparisons through an independent samples Student's t-test.
P-values are adjusted according to a Benjamini Hochberg false discovery rate analysis.
**Statistically significant speed effect ($p < 0.05$).*
†Statistically significant group effect ($p < 0.05$).
‡Statistically significant group × speed interaction ($p < 0.05$).

In the *post hoc* comparisons RFS demonstrated a significantly greater [$F_{(2,5)}$ = 7037, $p < 0.001$] duty factor compared to the MFS runners.

DISCUSSION

In the current study, we examined the effect of speed on the FSI and contact time for RFS and MFS runners. Out of all 47 investigated participants, 31 (66%) were rearfoot striking at the initial examined speed (i.e., 2.5 ms^{-1}) and 16 (34%) were mid- or forefoot striking. Only six participants (13%) exhibited a change in the FSP: three changed their FSP from RFS to MFS and three changed to a RFS while starting with a MFS. The rest of the participants did not change their initial FSP by increasing running speed. Further, we detected an overall decrease of FSI in the MFS group at higher running velocities. Both groups significantly decreased contact times with increasing speeds, however, the decrease was higher in the RFS group.

We hypothesized an increase of FSI in the RFS runners leading to a higher percentage of MFS runners by increasing running speed. Since only three participants changed from RFS to MFS our first hypothesis has been rejected. However, based on our use of the FSI, it was also shown that RFS runners do not alter the way their point of first contact within their chosen pattern either. This means they are maintaining a similar way of striking the ground throughout the examined speeds. In bipedal locomotion contact times decrease with increasing velocities (Gatesy and Biewener, 1991; Arampatzis et al., 2000) and RFS pattern is reported to have longer contact times than MFS (Hayes and Caplan, 2012; Di Michele and Merni, 2014; Ekizos et al., 2018). This could naturally lead participants that use RFS at lower velocities to change their strike pattern toward the fore of the foot. Dynamic stability during locomotion is a *sine qua non* concept and acute changes in the mechanics of running can cause instabilities in the system. In previous studies we found that acute changes in foot strike patterns (i.e., alteration from RFS to MFS) decrease the human dynamic stability during running (Ekizos et al., 2017, 2018). Maintenance of locomotor stability might be therefore a reason for the preservation of the foot strike patterns despite the increased running speed. Although contact time decreased significantly with the increased speed, the majority of the investigated RFS runners (87%) maintained the same FSP and minimized the changes in the FSI.

Midfoot strike runners also maintained their initial FSP throughout the examined speeds. However, in the MFS runners we found a significant (16.8%) decrease in the FSI with increasing speeds, which resulted in smaller differences in the FSI between RFS and MFS. This highlights that while the overall FSP did not change, the modification of the FSI within the MFS pattern indicates changes in the running strategy. At the same running speed, lower FSI is associated with a longer contact time (Gruber et al., 2013; Di Michele and Merni, 2014; Ekizos et al., 2018) and therefore the decrease of the contact time by increased speed was lower in MFS. The consequence was a reduction of the differences in the contact time between RFS and MFS runners by increasing speed. Both groups increased cadence and step length, and decreased step time in a similar way (**Table 1**). The flight time and consequently the duty factor on the other hand showed a different trend between groups indicating a greater time on the ground of the RFS runners by increasing speeds. There is evidence that the rate of metabolic energy consumption per body weight of running is inversely proportional to contact time (Kram and Taylor, 1990; Kram, 2000). Therefore, the lower decrease of contact time in MFS could affect the energy cost of running.

The higher FSI in the MFS group results in distinct distributions of the muscular output in the lower extremities between RFS and MFS runners [i.e., higher moments at the ankle and lower moments at the knee joint for MFS (Kulmala et al., 2013; Kuhman et al., 2016)], and leads to improvements in the cost coefficient (Ekizos et al., 2018). However, the improved cost coefficient due to the higher FSI in MFS did not improve running economy because of the lower contact time and thus greater rate of ground reaction force development (Ekizos et al., 2018). Traditionally, running economy is investigated in running speeds between 2.5 and 4 ms^{-1} (Heise and Martin, 2001; Arampatzis et al., 2006; Albracht and Arampatzis, 2013; Gruber et al., 2013; Craighead et al., 2014; Bohm et al., 2019) or as a percentage of the lactate threshold (Fletcher et al., 2009; Andersson et al., 2021) and several studies reported no differences in running economy between RFS and MFS (Gruber et al., 2013; Ekizos et al., 2018). In these speeds the average differences in the contact time between the investigated RFS and MFS were ~9.6% and reduced to 6.5% in the 5.0 ms^{-1} speed and may decrease the negative effect of the contact time for running economy in MFS. Elite distance runners, for instance, who are commonly employing speeds >5.0 ms^{-1} (Hoogkamer et al., 2017) might have energetic benefits using MFS patterns. At least, our findings indicate that the investigation of running economy between RFS and MFS should be extended to higher running speeds.

Here, we found that most runners maintain their initial FSP with increasing running speed and that MFS runners even move the point of force application to the posterior. This means that until 5.0 ms^{-1} it is possible to increase the rate of force generation without a transition to a more anterior point of force application. However, based on our results we cannot answer how the FSI or other parameters will develop at speeds above 5.0 ms^{-1}. Future investigations could improve our understanding concerning the effects of FSP on running mechanics and energetics during increased speeds, by considering measurements on metabolic energy consumption, lower leg kinetics and muscle mechanics (Arampatzis et al., 2006; Gruber et al., 2013; Bohm et al., 2019, 2021), as well as including runners who are accustomed with speeds higher than 5.0 ms^{-1}.

CONCLUSION

Although the majority of runners maintained their original FSP with increasing speed, we found that RFS and MFS runners employed different strategies to cope with this increase. Specifically, RFS runners maintained a similar FSI throughout the examined speeds, but MFS runners exhibited a significant reduction in the FSI, without this reduction being enough to change the FSP. Compared to RFS, the MFS group also decreased contact times slower with increasing speeds which could affect the measurement of the energy consumption in MFS runners, when this is measured only in slow speeds.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Humboldt-Universität zu Berlin. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AE designed the study, carried out the experiments, and drafted the manuscript. AS designed the study, carried out the experiments, and edited the manuscript. AA designed the study and drafted the manuscript. All authors gave final approval for publication.

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The Ratio of Oxygen Uptake From Ventilatory Anaerobic Threshold to Respiratory Compensation Point Is Maintained During Incremental Exercise in Older Adults

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Introduction: The period from ventilatory anaerobic threshold (VAT) to respiratory compensation point (RCP) during incremental exercise (isocapnic buffering phase) has been associated with exercise tolerance and skeletal muscle composition. However, several reports compare younger and older healthy adults, and specific age-related changes are unclear. This study aimed to examine the oxygen uptake (VO_2) from VAT to RCP and its change over time in younger and older healthy adults.

Methods: A total of 126 consecutive participants were divided into two groups (95 younger and 31 older than 50 years of age) who underwent cardiopulmonary exercise testing, and VAT and RCP were determined. The ratio (RCP/VAT) and difference (ΔVO_2 RCP-VAT) were calculated from the VO_2 of VAT and RCP and compared between groups and ages. Statistical analyses included *t*-tests and Spearman's correlation tests, and the significance level was set at <5%.

Results: RCP/VAT was not significantly different (1.40 ± 0.19 vs. 1.59 ± 0.24, $p = 0.057$) but weakly correlated with age ($r = -0.229$, $p = 0.013$, $y = -0.0031x + 1.7588$, lowering rate: 0.185%/year). Conversely, ΔVO_2 RCP-VAT was significantly lower in the older group (7.7 ± 3.1 vs. 13.8 ± 4.9 ml/kg/min, $p < 0.001$) and correlated significantly with age ($r = -0.499$; $p < 0.001$; $y = -0.1303x + 16.855$; lowering rate, 0.914%/year).

Conclusion: ΔVO_2 RCP-VAT was considered to be a poor indicator of lactate buffering capacity in the IB phase because both VAT and RCP were greatly affected by age-related decline. Conversely, RCP/VAT was suggested to be an index not easily affected by aging.

Keywords: isocapnic buffering phase, ventilatory anaerobic threshold, respiratory compensation point, aging, oxygen uptake, cardiopulmonary exercise testing

INTRODUCTION

In cardiac rehabilitation settings, exercise tolerance is generally assessed by cardiopulmonary exercise testing (CPET) using a combination of incremental exercise testing and expiratory gas analysis (Mann et al., 2013; Mezzani et al., 2013; JCS Joint Working Group, 2014; Price et al., 2016). The ventilatory anaerobic threshold (VAT) is the point at which carbon dioxide excretion (VCO_2) increases in response to an increase in oxygen uptake (VO_2) (Sullivan and Cobb, 1990; Nishijima et al., 2017, 2019). The respiratory compensatory point (RCP) is the point at which the exercise intensity increases and excessive carbon dioxide excretion by respiratory compensation begins due to accumulation of H^+ ions (Balady et al., 2010). The RCP is partially dependent on the chemosensitivity of the carotid bodies and the accumulation of lactate during incremental exercise (Takano, 2000). Between the VAT and RCP is the isocapnic buffering phase (IB phase) in which the increased lactate is buffered by bicarbonate (Beaver et al., 1986a; Wasserman et al., 2012; Yen et al., 2015).

During the IB phase, oxygen uptake increases relative to ventilation (VE/VO_2); however, carbon dioxide excretion does not (VE/VCO_2). The IB phase is a period of lactate buffering activity because the lactate produced by exercise is buffered and utilized *in vivo*; it is therefore thought to be related to the lactate steady state without rapid acidosis (Dekerle et al., 2003; Keir et al., 2018; Iannetta et al., 2019). In athletes, the IB phase is further associated with maximal oxygen uptake, a criterion for exercise tolerance (Korkmaz Eryılmaz et al., 2018), and patients with coronary artery disease show a similar relationship (Yen et al., 2018). However, it has been reported that the IB phase is shorter in older individuals (Lenti et al., 2011).

In previous reports, the time in the IB phase (Tanehata et al., 1999; Nakade et al., 2019) and ΔVO_2 RCP-VAT (Lenti et al., 2011; Carriere et al., 2019) have been used to define the IB phase; however, exercise tolerance indices such as peak VO_2 decline with age. The time can only be compared with the same protocol [it may be possible to adjust it; however, an adjustment is not desirable because of the errors in the load acceleration and oxygen uptake (Hansen et al., 1987)]. Thus, ΔVO_2 can be used to compare similar groups or those within the same age group; however, changes cannot be considered due to aging. It is not clear whether the shortening and decline in the indices of the IB phase used in the past are characteristically caused by aging or to what extent the decline is due to age-related changes. In the present study, we hypothesized that the ratio of oxygen uptake between RCP and VAT could be used as an indicator of IB phase because it can show how much oxygen uptake increases from VAT to RCP. By assessing the ratio of RCP to VAT, it would also be possible to easily show the lactate buffering capacity, and if it is the ratio of RCP to VAT oxygen uptake, it would be possible to make comparisons between ages.

Therefore, this study aimed to use the results of CPET to identify differences and changes over time in the IB phase using RCP/VAT and ΔVO_2 RCP-VAT in healthy younger and older participants.

MATERIALS AND METHODS

There were 126 healthy adult participants who completed a symptom-limited CPET in our hospital, for whom the VAT and RCP could be identified. Participants of previous studies (Kominami et al., 2015, 2021) and those who underwent screening tests at our hospital were enrolled; none of them had any diseases or had been treated with medications for indications such as cardiovascular or respiratory diseases. They were divided into two groups: <50 years ($n = 95$) and >50 years of age ($n = 31$). The participants' characteristics are presented in **Table 1**.

Exercise Testing

Cardiopulmonary exercise testing was performed using a stationary bicycle (StrengthErgo 8; Mitsubishi Electric Engineering, Tokyo, Japan) and a breath-by-breath gas analyzer (AE-300S; Minato Ikagaku Co., Tokyo, Japan). Symptomatic maximal exercise was performed using a ramp protocol of 5–30 watts (W)/min according to age and condition after 2–3 min rest and warm-up of 0–10 W lasting 2–3 min. Rating of perceived exertion (RPE) at the end of the exercise was assessed using the Borg scale (Beaver et al., 1986a; Takano, 2000; Dekerle et al., 2003; Balady et al., 2010; Lenti et al., 2011; Wasserman et al., 2012; Yen et al., 2015, 2018; Nishijima et al., 2017, 2019; Keir et al., 2018; Korkmaz Eryılmaz et al., 2018; Carriere et al., 2019; Iannetta et al., 2019; Nakade et al., 2019).

Expiratory Gas Analysis Index

Ventilatory Anaerobic Threshold

The VAT was visually determined using the modified V-slope method as described by Sue et al. (1988), which is a modification of the method described by Beaver et al. (1986b).

The ventilatory equivalent method (the point at which VE/VO_2 begins to rise without an increase in VE/VCO_2) and end-tidal methods ($PetO_2$ begins to rise without a decrease in $PetCO_2$) was used as a complement (Balady et al., 2010; Wasserman et al., 2012).

Respiratory Compensation Point

Respiratory compensation point was comprehensively determined from the point where $PetCO_2$ decreased, VE/VCO_2 began to increase, and the inflection point of the VE/VCO_2 slope.

The values of VAT VO_2 and RCP VO_2 were used to calculate RCP/VAT and ΔVO_2 RCP-VAT (**Figures 1A,B**).

VE/VCO_2 Slope

VE/VCO_2 slope as ventilation efficiency during incremental exercise load was calculated as the slope of linear regression from the start of exercise to RCP.

Oxygen Uptake Kinetics ($\Delta VO_2/\Delta$Work Rate)

The VO_2–work rate relationship during ramp exercise testing was evaluated by plotting the work rate on the x-axis and VO_2 on the y-axis (Hansen et al., 1987; Wasserman et al., 2012). Both maximal and submaximal exercise data were plotted on the same graph. The initial time delay was removed from the analysis

TABLE 1 | Participants' clinical characteristics.

		All	Young (<50 years)	Older (≥50 years)
		n = 126	*n* = 95	*n* = 31
Age	(years)	35.5 ± 20.5	24.0 ± 6.3	68.6 ± 6.5*
Sex	(male:female)	88:38	71:24	17:14
Height	(cm)	167.5 ± 8.9	170.0 ± 8.2	160.0 ± 6.1*
Body weight	(kg)	62.7 ± 10.7	63.8 ± 10.6	59.5 ± 10.5
BMI		22.3 ± 2.8	22.0 ± 2.7	23.1 ± 3.1

Data are presented as mean ± standard deviation. BMI, body mass index.
**Significant ($p < 0.05$) for younger vs. older group.*

(Hansen et al., 1987). Each slope was calculated using linear regression for the maximum tests.

Statistical Analysis

Data are presented as the mean ± standard deviation. Statistical analyses were performed using Statistics for Excel 2012 (Social Survey Research Information Co., Tokyo, Japan). Student's *t*-test was used for comparisons between the two groups. Pearson's correlation coefficient was used to determine the correlation between age and each parameter, and the lowering rate with age was calculated from the regression coefficient of the regression line. The 95% confidence intervals and prediction intervals were also calculated for the relationship between age and RCP/VAT, ΔVO_2/weight RCP-VAT, VAT VO_2/weight, and RCP VO_2/weight. The significance level was set at 5%.

Ethical Considerations

This research was conducted in accordance with the code of ethics of Sapporo Ryokuai Hospital and with due consideration for the protection of the participants' personal information. Informed consent was obtained from all participants for their participation in the study and for publication of this report. The data obtained were de-linked and anonymized, and this study was conducted using the data for analysis. The authors confirmed that all participants could not be identified and that they were fully anonymized. Furthermore, the authors affirm that all mandatory health and safety procedures were complied within the course of conducting any experimental work reported in this paper.

RESULTS

No adverse events such as arrhythmia, angina pectoris, or worsening of heart failure requiring treatment occurred

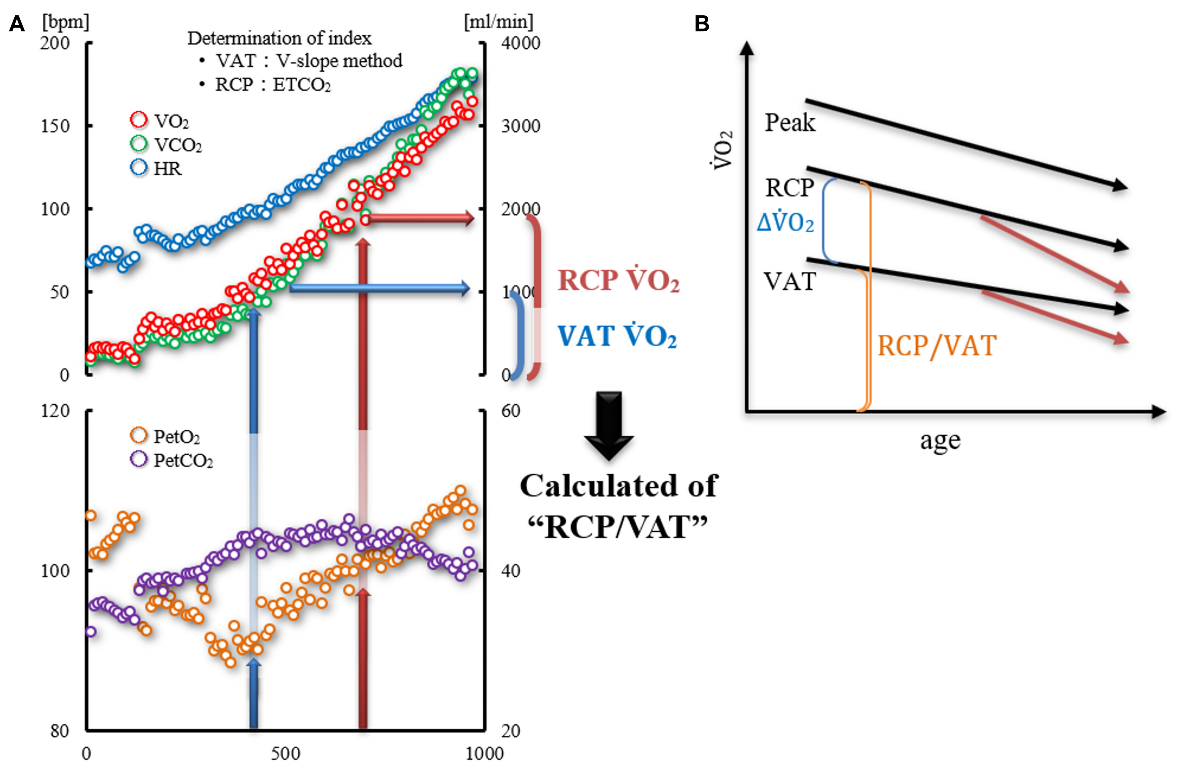

FIGURE 1 | (A,B) Diagram showing the calculation of "RCP/VAT". **(A)** Time trends of HR, VO_2, VCO_2, $PETO_2$, and $PETCO_2$ in one case. VAT was determined using the V-slope method and RCP from $PETCO_2$ and VE/VCO_2 slope. The RCP/VAT was calculated by dividing the RCP VO_2 by the VAT VO_2. **(B)** Age-related changes of VAT, RCP, and Peak VO_2 (three black allows). It is believed that the decline in VAT is slower than that in RCP due to aging. Therefore, ΔVO_2 RCP-VAT decreases with age; however, RCP/VAT may not change with age. If a disease associated with chronic inflammation, such as heart disease, develops, both VAT and RCP may further decrease, as shown by the red arrows, as well as ΔVO_2 RCP-VAT and RCP/VAT.

TABLE 2 | Primary cardiopulmonary data during exercise.

		All *N* = 126	Young (<50 years) *N* = 95	Older (>= 50 years) *N* = 31	Effect size (r)
Peak VO_2	(ml/min)	2173 ± 714	2434 ± 609	1390 ± 327*	0.626
Peak VO_2/weight	(ml/kg/min)	34.4 ± 9.0	38.0 ± 6.9	23.6 ± 4.7*	0.692
Peak HR	(bpm)	168 ± 21	178 ± 11	140 ± 20*	0.776
Peak R		1.22 ± 0.10	1.24 ± 0.10	1.17 ± 0.08	0.297
RPE; dyspnea		15.5 ± 2.1	15.9 ± 1.8	14.1 ± 2.4*	
RPE; leg fatigue		17.1 ± 1.8	17.5 ± 1.4	15.7 ± 2.3*	
VAT VO_2	(ml/min)	1058 ± 336	1161 ± 315	746 ± 153*	0.539
VAT VO_2/weight	(ml/kg/min)	16.9 ± 4.4	18.3 ± 4.0	12.7 ± 2.6*	0.542
VAT HR	(bpm)	112 ± 18	119 ± 15	93 ± 11*	0.632
VAT R		0.86 ± 0.06	0.86 ± 0.06	0.87 ± 0.05	0.096
RCP VO_2	(ml/min)	1758 ± 544	1925 ± 486	1170 ± 253*	0.578
RCP VO_2/weight	(ml/kg/min)	29.3 ± 7.9	32.0 ± 6.3	20.0 ± 5.5*	0.610
RCP HR	(bpm)	149 ± 22	158 ± 15	119 ± 17*	0.730
RCP R		1.06 ± 0.06	1.07 ± 0.06	1.03 ± 0.06	0.218
RCP/VAT		1.65 ± 0.27	1.68 ± 0.28	1.56 ± 0.21	0.205
$\Delta VO_2/\Delta WR$		10.7 ± 1.0	10.7 ± 1.0	10.8 ± 1.0	0.050
VE/VCO_2 slope		23.8 ± 4.0	22.3 ± 2.9	28.1 ± 3.6*	0.629
$PetCO_2$ at rest	(mmHg)	36.4 ± 3.6	37.4 ± 3.4	33.5 ± 2.6*	0.470
$PetCO_2$ at VAT	(mmHg)	44.1 ± 4.4	45.6 ± 3.7	39.5 ± 3.2*	0.598
$PetCO_2$ at RCP	(mmHg)	45.3 ± 5.2	46.7 ± 4.5	40.1 ± 4.0*	0.533
$PetCO_2$ RCP – rest	(mmHg)	8.8 ± 3.6	9.3 ± 3.6	6.6 ± 2.6*	0.317
VD/VT at rest	(%)	39.7 ± 4.9	38.5 ± 4.9	42.9 ± 3.1*	0.395
VD/VT at VAT	(%)	30.2 ± 4.5	28.6 ± 3.5	34.9 ± 3.6*	0.618
VD/VT at RCP	(%)	25.5 ± 3.9	24.1 ± 2.9	30.1 ± 3.3*	0.645
VD/VT RCP – rest	(%)	−13.9 ± 4.3	−14.3 ± 4.4	−12.7 ± 3.5	0.160

Data are presented as mean ± standard deviation. VO_2, oxygen uptake; VCO_2, carbon dioxide; VE, minute ventilation; $PETCO_2$, end-tidal carbon dioxide pressure; VD/VT, dead-space gas volume to tidal volume ratio; AT, anaerobic threshold; RCP, respiratory compensation point; HR, heart rate; RPE, rating of perceived exertion; WR, work rate; R, respiratory exchange rate.
**Significant ($p < 0.05$) for younger vs. older group.*

during CPET. Regarding the characteristics of the participants, there were no significant differences in sex, weight, or BMI (**Table 1**).

Cardiopulmonary Exercise Testing Parameters

Each parameter in the CPET is listed in **Table 2**. Compared with the younger group, the older group showed significantly lower values of VAT and RCP VO_2 ($p < 0.001$, respectively). Moreover, $PetCO_2$ was significantly lower in the elderly group, and the VE/VCO_2 slope was significantly higher ($p < 0.001$, respectively).

Furthermore, both ΔVO_2/weight RCP-VAT and RCP/VAT showed a significant correlation with Peak VO_2 ($r = 0.629$, $p < 0.001$ and $r = 0.217$, $p = 0.017$, respectively).

Respiratory Compensation Point/Ventilatory Anaerobic Threshold and ΔVO_2/Weight Respiratory Compensation Point-Ventilatory Anaerobic Threshold

There was no significant difference in RCP/VAT between the younger and older groups (**Table 2** and **Figure 2**). The coefficient of the linear regression equation was −0.0031, and the annual rate of decline was 0.185%, indicating that the effect of aging was not significant. ΔVO_2/weight RCP-VAT was significantly lower in the older group, and age-related changes showed moderate negative correlation. The coefficient of the linear regression equation was −0.1303, and the annual rate of decline was 0.914%, indicating a significant effect of age-related changes.

DISCUSSION

In this study, IB during incremental exercise load was expressed as a ratio of oxygen uptake, which is different from that in previous studies. Moreover, the differences between healthy younger and elderly subjects and the changes over time were investigated. During the IB period from VAT to RCP, as the exercise intensity increases, lactate is buffered by HCO_3^-. Thus, a longer IB phase is less likely to lead to metabolic acidosis, allowing for the high-intensity exercise to continue for longer. Conversely, a short IB phase or an early onset of RCP may be associated with shortness of breath and fatigue. Our results show that the ratio of oxygen uptake

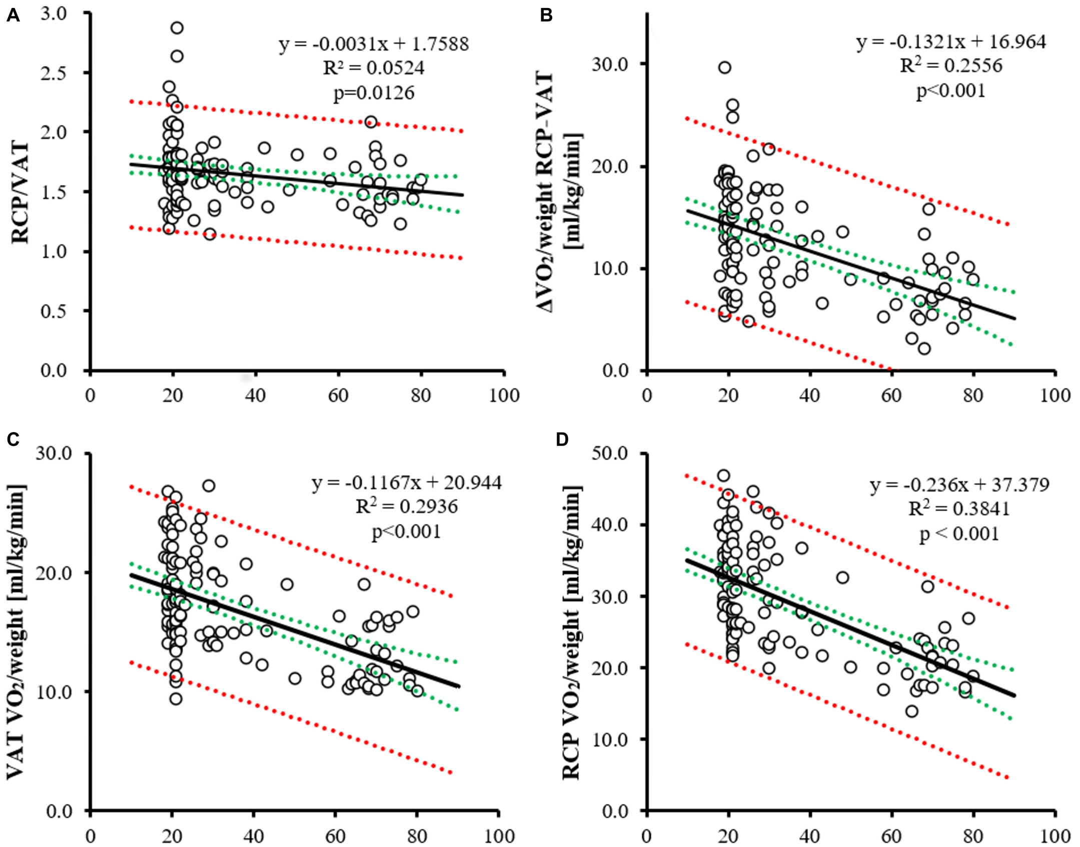

FIGURE 2 | Age–related change of RCP/VAT, VO_2/weight RCP-VAT, VAT and RCP VO_2/weight. The age-related change of RCP/VAT **(A)**, VO_2/weight RCP-VAT **(B)**, VAT **(C)** and RCP VO_2/weight **(D)**. The horizontal axis indicates age. For each panel, the correlation coefficient (linear regression equation and lowering rate per year; black line), 95% confidence intervals (red dotted line), and prediction intervals (green dotted line) are shown.

during IB (RCP/VAT) is not significantly different in healthy older adults compared to healthy younger adults and is a modest indicator compared to the decline in VAT, RCP, and ΔVO_2 RCP-VAT.

Age-Related Changes in Respiratory Compensation Point/Ventilatory Anaerobic Threshold

In this study, the decrease in VAT and RCP VO_2/weight was −8.8 and −16.2 ml/min/year (−0.118 and −0.242 ml/kg/min/year, 0.627 and 0.722%/year), respectively, which was comparable to that reported in previous studies (Itoh et al., 2013). Similarly, the ΔVO_2/weight RCP-VAT decreased with age. VAT is detected in CPET by the excretion of carbon dioxide in the exhaled air due to the buffering of lactate, which is produced by increased glycolysis associated with increased exercise intensity. The presence of increased lactate in the blood and carbon dioxide excretion in the exhaled air is well correlated, though there is a time delay. This association is derived from the proportion of slow-twitch fibers in skeletal muscle and CO_2 storage *in vivo* (Ivy et al., 1980). The RCP is the period from the VAT through the IB phase to the onset of respiratory compensation. The buffering capacity of CO_2/H^+ produced by lactate is influenced by the fiber type in skeletal muscle; previous studies have shown an association with skeletal muscle composition, particularly type 2 fibers (Nakagawa and Hattori, 2002).

Several mechanisms are believed to allow the organism to rapidly maintain homeostasis in response to dynamic exercise (Bruce et al., 2019). The excretion of carbon dioxide during expiration is related to pulmonary blood flow, that is, cardiac output and ventilatory capacity. In our study, $PETCO_2$, a measure of cardiac output, was significantly lower in the older group (though cardiac output was not measured directly and may therefore be dissociated from actual measurements). Additionally, the VE/VCO_2 slope was higher in the older group, which may have contributed to the reduced capacity for lactate buffering and carbon dioxide excretion up to RCP, and the higher rate of decline in RCP VO_2 than VAT with age.

In addition, $\Delta VO_2/\Delta WR$, which indicates the oxygen utilization capacity of the peripheral motor muscle group, was not affected by age. In patients with specific risk factors, the reduced oxygen availability of the peripheral motor musculature facilitates anaerobic energy production during exercise, leading to the production of lactic acid and the buffering and excretion of CO_2. In patients with heart failure, a decrease in cardiac output and vasodilatory capacity limits blood flow to peripheral exercise muscle groups, leading to a decrease in $\Delta VO_2/\Delta WR$. In the present study, $\Delta VO_2/\Delta WR$ was not affected by aging, suggesting that the effect on energy production was small. However, we were not able to investigate related factors such as circulating blood volume, total body skeletal muscle mass, muscle composition, and plasma bicarbonate ion concentration concerning the accumulation and buffering capacity of CO_2/H^+ produced *in vivo*.

The results of this study showed that various indices of exercise (e.g., peak VO_2 and VAT) decreased with age, and the rate of decrease was higher for RCP than for VAT. RCP/VAT, the ratio of RCP VO_2 to VAT VO_2, showed a modest negative correlation over time; however, there was no significant difference in RCP/VAT between the younger and older groups. RCP/VAT is considered a more moderate indicator of the effect of aging than ΔVO_2/weight RCP-VAT. The results suggest that the ability to excrete CO_2 produced *in vivo* or to accumulate and buffer CO_2 is less affected by aging.

Respiratory Compensation Point/Ventilatory Anaerobic Threshold and ΔVO_2 Respiratory Compensation Point-Ventilatory Anaerobic Threshold and Isocapnic Buffering Phase Time

For some IB phases that have been used in the past, the IB phase time can only be used for comparison in the same protocol. In addition, when the IB phase is expressed by ΔVO_2/weight RCP-VAT, it is not possible to determine whether the decrease is only in that part of the whole exercise or the whole exercise, given that it is a cut-off of the oxygen uptake during exercise. In fact, as in a previous study (Carriere et al., 2019), peak VO_2 and ΔVO_2/weight RCP-VAT were correlated; however, since ΔVO_2/weight RCP-VAT decreases with age, it is not suitable for comparison between groups of different ages. Conversely, the ratio of oxygen uptake, such as RCP/VAT, shows that the balance of exercise tolerance indices is maintained, though overall exercise tolerance decreased.

At low exercise intensities, oxidative phosphorylation is the main source of ATP production. As the exercise intensity increases, glycolysis increases, leading to lactate production and buffering. When the RCP is exceeded, lactic acidosis occurs. Since mitochondrial function including oxidative phosphorylation is not affected by aging or is only mildly affected (Lanza et al., 2005), VAT is considered to be less susceptible to the decline in mitochondrial function, except in certain diseases.

For a practical recommendation, by combining data with VAT and RCP VO_2 and ΔVO_2/weight RCP-VAT, we believe that RCP/VAT can possibly be used as a concise indicator for lactate buffering capacity and skeletal muscle composition ratio.

Research Limitations

This study had several limitations. First, because the analysis was based on only exhaled gas analysis, hematological parameters such as blood levels of lactate and bicarbonate ions, as well as hemodynamics, could not be evaluated in parallel. RCP is associated with maximal lactate steady state, and exercise therapy improves skeletal muscle function (oxidative capacity); however, in this study, it was difficult to clarify what led to the increase and improvement in RCP/VAT with exercise therapy. Second, RCP/VAT is an index that can be influenced by either an increase or decrease in one of the indices; a decrease in VAT may result in an increase in RCP/VAT. Third, the relationship with prognosis, as shown by IB phase time and ΔVO_2/weight RCP-VAT, is unclear. Fourth, the effect of the degree of training on the lactate buffering capacity is unknown because we did not investigate the activity level or the degree of training in all participants. Finally, due to the small number of cases in the 30–60 age range, there is insufficient analysis of trends by age and by age group.

CONCLUSION

The ratio of oxygen uptake from VAT to RCP was not significantly lower in healthy older participants than in healthy younger participants. Although exercise tolerance decreases with age, age does not have a robust effect on lactate buffering capacity on exercise tolerance.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

KK and MA: conceptualization and methodology. KK: data curation, formal analysis, project administration, software, validation, visualization, and writing – original draft. MA: funding acquisition, resources, and supervision. KK, KI, TK, and MM: investigation. KI, TK, MM, and MA: writing – review and editing. All authors contributed to the article and approved the submitted version.

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The Performance-Result Gap in Mixed-Reality Cycling – Evidence From the Virtual Tour de France 2020 on Zwift

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Background: Mixed-reality sports are increasingly reaching the highest level of sport, exemplified by the first Virtual Tour de France, held in 2020. In road races, power output data are only sporadically available, which is why the effect of power output on race results is largely unknown. However, in mixed-reality competitions, measuring and comparing the power output data of all participants is a fundamental prerequisite for evaluating the athlete's performance.

Objective: This study investigates the influence of different power output parameters (absolute and relative peak power output) as well as body mass and height on the results in mixed-reality competitions.

Methods: We scrape data from all six stages of the 2020 Virtual Tour de France of women and men and analyze it using regression analysis. Third-order polynomial regressions are performed as a cubic relationship between power output and competition result can be assumed.

Results: Across all stages, relative power output over the entire distance explains most of the variance in the results, with maximum explanatory power between 77% and 98% for women and between 84% and 99% for men. Thus, power output is the most powerful predictor of success in mixed-reality sports. However, the identified performance-result gap reveals that other determinants have a subordinate role in success. Body mass and height can explain the results only in a few stages. The explanatory power of the determinants considered depends in particular on the stage profile and the progression of the race.

Conclusion: By identifying this performance-result gap that needs to be addressed by considering additional factors like competition strategy or the specific use of equipment, important implications for the future of sports science and mixed-reality sports emerge.

Keywords: mixed-reality, cycling, result prediction, power output, elite athletes, competition

INTRODUCTION

Mixed-reality sports platforms such as Zwift allow the athletic performance provided in the real world to be transferred into a virtual space so that the participating athletes can also physically interact and even compete with each other (Speicher et al., 2019; Westmattelmann et al., 2021a). Driven by the Covid-19 pandemic, mixed-reality sports have reached the highest level of sports in a very short time, with the first-ever Virtual Tour de France held in July 2020 (Westmattelmann et al., 2021a). Both the women's and men's races, which were hosted on the indoor cycling platform Zwift, featured professional road cyclists (Westmattelmann et al., 2021b). In the men's race, several "real-world" Tour de France overall winners and stage winners participated (Cyclingnews, 2020). The races gained a lot of public attention and were broadcast in over 130 countries (Cyclingnews, 2020). The fact that in December 2020, the world cycling federation (UCI) for the first time hosted the "UCI Cycling Esports World Championships" reflects the rising interest from sports organizations (UCI, 2020). In addition to participating in competitions, professional cyclists use mixed-reality sports platforms for training or social interaction (Westmattelmann et al., 2021c).

In mixed-reality cycling races, the speed of the avatar within the virtual world depends on the physical power generated (in watts), in addition to the athlete's body mass and height (Delaney and Bromley, 2020). Cycling power is measured through a so-called smart trainer on which the athlete's road bike is mounted. Besides physical performance, the avatar's speed may also depend on additional factors like slipstream effects, simulated course profiles or virtual equipment. Additionally, so-called power-ups are available, whose strategic use may also affect the race results. Mixed-reality sports platforms use a number of implemented algorithms to define how athletic performance on the smart trainer is transferred to the virtual world and can be analogously compared to the laws of nature in the real world. Similarly, rolling resistance, aerodynamic drag, and the movement on mixed-reality sports platforms are also simulated according to defined rules (Kyle, 2003). In both the real world and the virtual world, knowledge of all relevant parameters, such as power output or body mass and height of the rider and course characteristics, could be used to accurately determine the speed or riding time over a defined course in individual time trials. In mass-start races, such as the (Virtual) Tour de France, the behavior of the riders and the associated interaction (e.g., slipstream) lead to an emergent system behavior that is not represented by the laws of nature (real world) or is not included in the algorithm on mixed-reality sports platforms (virtual world).

Given the complex interplay of various factors that may be critical to success in cycling races, exercise physiology research can be divided into two domains. The first domain focuses on factors that influence the physical performance of athletes in endurance sports, which in cycling is measured as absolute power in watts or relative power in watts per kilogram body weight. In their review, Jeukendrup and Martin, (2001) summarized factors that determine performance in cycling and ranked them in order of importance. According to their study, the greatest impact on cycling performance originates from the internal factor training, particularly a training program. They also valued altitude training as having a positive impact on performance. Particularly in the context of indoor cycling, the starting strategy (Mattern et al., 2001), the time of day (Atkinson et al., 2005), warm-up (Munro et al., 2017), recovery duration (Glaister et al., 2005), and precooling strategy (Quod et al., 2008) could also be considered as factors influencing performance. In cycling, the seating position (standing or seated) also influences performance (Hansen and Waldeland, 2008). Furthermore, gear ratio and pedaling cadence have a direct impact on cycling economy/efficiency (Faria et al., 2005). Finally, Atkinson et al. (2003) identified the athletes' nutritional strategy before, during, and after a race as a determinant of performance in addition to the factors mentioned so far.

In the second domain, sports physiology literature discusses numerous factors - like physical performance delivered by the athlete - that can predict the outcome of competitions or the sporting success of an athlete (Alvero-Cruz et al., 2019; Sousa et al., 2021). Race success correlates with the peak power an athlete is able to perform in a laboratory test (Faria et al., 2005). Thus, it can be noted that the outcome of a cycling race depends on power-to-weight characteristics (Gallo et al., 2021; Lee et al., 2002). Van Erp and Sanders, (2020) show that in professional cycling races maximum mean power over shorter durations (<5 min) are higher for riders who are placed in the top-10 of a race than for riders who are not in the top-10. In addition to physiological parameters, factors such as the bike mass and body mass (both are particularly important in the mountains; Jeukendrup and Martin, 2001) as well as aerodynamic components such as body position, bike frame, and wheels can affect the competition result (Faria et al., 2005; Malizia et al., 2021). Based on their machine learning approach, Kholkine et al. (2020) assume that factors such as weather, team strategy, road conditions, or mechanical failure must be included when predicting a competition result. Another study by Van Erp et al. (2021b) showed that a cyclists' position in the peloton could be an indicator for the result of a stage at the Tour de France. In terms of para-cyclists' performance, Wright, (2016) also found that pacing strategy improves athletes' performance in short time trials on cycling track.

To summarize the current state of research in the two domains, we can state that the factors determining an athlete's physical performance are widely known, particularly in cycling. In contrast, the effect of the physical performance delivered in competition on the competition result requires further research. Studies show that several factors, such as high peak power or high power-to-weight ratio, can influence the result in cycling races. However, the physical performance was mostly determined in laboratory tests with a time lag before or after the competition (e.g., Lee et al., 2002; Babault et al., 2018; Gallo et al., 2021). Thus, it is still unclear what influence the actual power output in the competition has on the competition result. Although performance in-competition data from professional athletes are increasingly available via platforms such as Strava, the quantity of available data is still insufficient to calculate the effect on the competition result (Sanders and Heijboer, 2019;

Van Erp and Sanders, 2020; Westlake, 2020; Van Erp et al., 2021a).

In mixed-reality competitions the performance data, body mass and body height of all participants are recorded and published. This happens for two reasons. First, without the disclosure of the recorded data, the athlete's avatar would not move in the virtual world, and thus the competition would not be possible. Second, the performance data of all participants are publicly available during and after the race for all participants and spectators and are even integrated into the broadcasts to increase transparency about the race result. It was shown that the relative power output in mixed-reality races in which professional athletes participated is comparable to the relative performances in professional road races (Westmattelmann et al., 2021b). Since mixed-reality races are generally shorter than road races, the performance delivered is more similar to real-world time trials or mountain top finishes (Westmattelmann et al., 2021b). Although mixed-reality competitions publish the in-competition performance data from all professional road cyclists participating in the same competition publicly, it is unclear whether critical performances over specific time periods are particularly more relevant to race results than other performance parameters.

Regarding this research gap, the aim of this study is to analyze the effect of different performance parameters and the rider's body mass and height on the results of mixed-reality competitions. In doing so, the following research question is addressed by analyzing in-competition data and results from the six stages of the women's and men's Virtual Tour de France: What influence do 1) absolute power over the entire distance, 2) relative power over the entire distance, 3) maximum relative power over 20 min, 4) maximum relative power over 5 min, 5) maximum relative power over 1 min, 6) maximum relative power over 30 s, 7) maximum relative power over 15 s, 8) body mass, and 9) body height of a rider have on the competition result (measured in riding time)?

The following section describes how the performance data for the different Virtual Tour de France stages 2020 are collected and analyzed. Subsequently, the influence of the in-competition performance parameters and the rider's body mass and height on the result is determined via polynomial regression analyses. The findings are discussed against the background of insights from sports physiology, and practical implications for the future of (mixed-reality) sports are presented. Finally, the main insights are summarized in the conclusion.

MATERIALS AND METHODS

Ethical Approval

This study was approved by the Ethics Committee of the School of Business & Economics of the University of Münster, Germany. Since only publicly available data from the Zwift Power platform was used, no informed consent was required from the athletes.

Experimental Design

Given the novelty of mixed-reality sport for exercise physiology science, we first provide an overview of the four phases of the experimental design (**Figure 1**).

Phase 1 marks the three weekends in July 2020 where the Virtual Tour de France took place. The performance data (absolute and relative power output) as well as body mass and height were integrated into the extensive broadcasting of the competitions and uploaded to the Zwift Power platform and are therefore publicly available, even after the end of the competitions. In phase 2, the athletes' performance data, body mass and height, and the corresponding results of the six stages of the Virtual Tour de France for women and men were obtained using the web scraping technique from Zwift Power. In phase 3, the different performance data, body mass and height were plotted with the competition result (measured in riding time) to visualize the relationship between the determinants (power output, body mass and height) and the competition result. In Phase 4, a cubic relationship was assumed based on the visualizations in phase 3. The influence of the determinants on the competition outcome was calculated using third order polynomial regressions to account for the cubic relationship. The following subsections are organized according to each of the four phases of the experimental design.

Virtual Tour de France

In July 2020, the cycling platform Zwift and the Amaury Sport Organisation (ASO) cooperatively hosted the first "Virtual Tour de France" (Tour de France, 2020b). In this event female and male professional cyclists competed for individual stage victories and overall team classifications in a total of six stages (Tour de France, 2020a). Unlike the real Tour de France, an annual event which is also organized by the ASO, the classifications (overall, youth, mountain, and sprint) were not awarded to individual riders but to the best teams. To have the highest chance of winning, the professional road cycling teams nominated four riders for each stage who were best suited to the different stage profiles (Schlange, 2020). Thereby, no male rider was allowed to race more than three and no female rider more than four stages in total. The different stages were won by the riders who completed the route in the shortest riding time. However, the avatar's speed and thus the competition result also depended on the use of so-called power-ups (e.g., the aero power-up makes a rider more aerodynamic for 15 s) or riding in the slipstream. The six stages of the Virtual Tour de France are partly modeled after the real Tour de France (for example, by recreating the Mont Ventoux climb or the circuit on the Champs-Élysées in Paris, Tour de France, 2020a). The route profiles of the stages of the Virtual Tour de France are illustrated in **Figure 2**.

Data Collection and Sample

To be able to analyze the influence of different performance indicators as well as body mass and height on the race results of the stages of the Virtual Tour de France, we scraped the performance data, body mass, body height, and the corresponding riding times from the platform Zwift Power (Ostanek, 2020). To do so, we used the web scraping tool Parsehub and scraped all six stages individually. Zwift Power collects different racing data for public races scheduled and performed on Zwift. After identifying the type of data relevant for our study, we used the .csv output file generated by

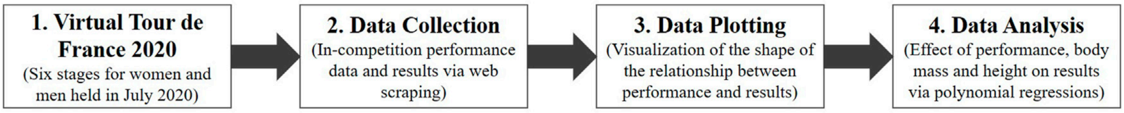

FIGURE 1 | Experimental design.

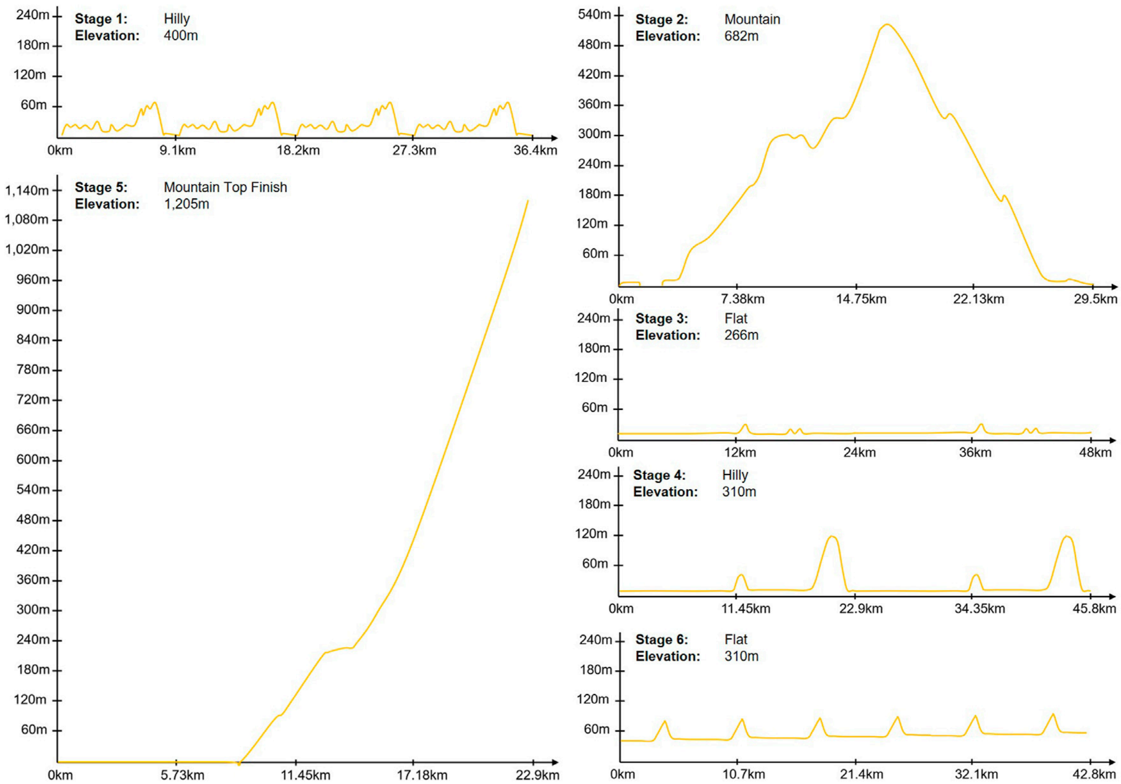

FIGURE 2 | Stage profiles Virtual Tour de France. Source: www.letour.fr.

Parsehub that contains the data to perform our analysis. For this study, the following data for all stages of the women's and men's races were retrieved: absolute power (watts) and relative power (w/kg) over the entire distance, as well as relative peak power over 20 min (w/kg_20m), 5 min (w/kg_5m), 1 min (w/kg_1m), 30 s (w/kg_30s), 15 s (w/kg_15s), body mass and height, average heart rate (HR_avg), and maximum heart rate (HR_max) over the entire race duration. Finally, riding times were retrieved, which are used as the dependent variable (competition success). Compared to the pure competition rankings, the metric scaling of the riding times accounts for differences between the ranks. The descriptive statistics of all athletes who finished the respective stage appear in the competition results and are shown in **Tables 1** and **2**. For each stage, the length, the elevation meters, and the winner's time are also presented.

The winning time in the different stages of the men's race ranged between 41 and 59 min. Accordingly, the length of the virtual stages corresponds more to that of a time trial, which in the Virtual Tour de France was 36.8 km long, and the winning time was 55 min (Sanders and Heijboer, 2019; Procyclingstats, 2020). Women raced the same distances as men in the Virtual Tour de France, with winning times ranging from 47 to 66 min.

Data Plotting

In road cycling, riders must overcome the forces of gravity, rolling resistance, and aerodynamic drag to move forward (Kyle, 2003). In particular, at a speed above 40 kph - which is exceeded in most professional races - the interaction of these three forces causes a cubic relationship between the power to be produced by the rider and the resulting speed, respectively riding time over a defined distance (Kyle, 2003). As mixed-reality platforms like Zwift seek to simulate speed as realistically as possible, the relationship between the performance parameters considered and the race outcome was visualized to gain initial insights on whether the

TABLE 1 | Descriptive statistics for participants of women's stages.

		Watts	W/kg	W/kg 20m	W/kg 5m	W/kg 1m	W/kg 30s	W/kg 15s	HR avg	HR Max	Body mass	Body height
Stage 1 Length: 36.4 km Elevation: 400 m Time: 0:45:17	N	33	33	33	33	33	33	33	22	22	29	28
	Mean	235	4.08	4.30	4.88	5.72	6.74	8.08	172	188	58.1	167.7
	SD	30	0.47	0.43	0.35	0.61	1.09	1.94	10	9	5.3	5.6
Stage 2 Length: 29.5 km Elevation: 682 m Time: 0:41:12	N	42	42	42	42	42	42	42	26	26	38	33
	Mean	224	4.13	4.56	5.05	5.99	6.86	8.04	172	187	54.3	166.3
	SD	26	0.52	0.47	0.62	0.85	1.35	1.87	10	10	5.4	6.2
Stage 3 Length: 48.0 km Elevation: 266 m Time: 0:59:24	N	33	33	29	29	29	29	29	19	17	26	24
	Mean	231	3.82	4.19	4.63	5.81	6.98	8.22	171	192	61.6	170.5
	SD	32	0.47	0.36	0.35	0.76	1.30	1.95	13	11	3.9	5.4
Stage 4 Length: 45.8 km Elevation: 310 m Time: 0:58:06	N	39	39	33	33	33	33	33	27	24	36	32
	Mean	226	3.97	4.55	5.07	6.10	7.35	8.80	170	192	57.5	168.3
	SD	32	0.53	0.38	0.43	0.57	1.24	2.05	12	10	5.5	6.3
Stage 5 Length: 22.9 km Elevation: 1205 m Time: 0:46:21	N	33	33	33	33	33	33	33	21	21	30	28
	Mean	238	4.43	4.72	5.11	5.88	6.37	6.82	170	188	53.8	166.4
	SD	31	0.59	0.49	0.52	0.80	1.05	1.35	24	11	5.1	5.5
Stage 6 Length: 42.8 km Elevation: 310 m Time: 0:51:44	N	29	29	29	29	29	29	29	23	23	28	26
	Mean	242	4.01	4.31	4.85	6.08	7.17	8.29	169	192	60.6	170.3
	SD	34	0.56	0.44	0.33	0.71	1.32	1.84	16	15	5.3	5.9

Note. Watts, absolute power in watts; W/kg, relative power in watt per kg bodyweight; W/kg 20m, relative peak power over 20 min; W/kg 5m, relative peak power over 5 min; W/kg 1m, relative peak power over 1 min; W/kg 30s, relative peak power over 30 s; W/kg 15s, relative peak power over 15 s; HR avg, average heartrate in beats per minute; HR max, maximum heartrate in beats per minute; body mass, rider's body mass in kilogram; height, rider's body height in centimeter; N, sample size; SD, standard deviation.

TABLE 2 | Descriptive statistics for participants of men's stages.

		Watts	W/kg	W/kg 20m	W/kg 5m	W/kg 1m	W/kg 30s	W/kg 15s	HR avg	HR max	Body mass	Body height
Stage 1 Length: 36.4 km Elevation: 400 m Time: 0:45:17	N	24	24	24	24	24	24	24	19	19	24	20
	Mean	338	4.88	5.29	5.89	7.17	8.87	10.05	171	188	69.3	181.2
	SD	46	0.57	0.39	0.43	0.86	1.74	2.32	10	9	5.1	5.2
Stage 2 Length: 29.5 km Elevation: 682 m Time: 0:41:12	N	25	25	25	25	25	25	25	16	16	24	18
	Mean	332	5.04	5.76	6.24	7.06	9.14	10.97	166	185	66.5	179.8
	SD	36	0.59	0.43	0.48	0.93	2.26	2.81	8	7	6.0	5.6
Stage 3 Length: 48.0 km Elevation: 266 m Time: 0:59:24	N	20	20	18	18	18	18	18	9	8	19	13
	Mean	314	4.41	4.87	5.51	6.75	7.54	8.49	155	181	70.8	184.6
	SD	54	0.69	0.55	0.46	0.86	1.43	1.92	19	10	7.9	5.3
Stage 4 Length: 45.8 km Elevation: 310 m Time: 0:58:06	N	27	27	23	23	23	23	23	14	12	25	21
	Mean	325	4.73	5.30	6.01	7.05	8.20	9.47	165	185	68.4	182.1
	SD	42	0.52	0.45	0.67	1.03	1.61	2.10	11	10	6.9	6.0
Stage 5 Length: 22.9 km Elevation: 1205 m Time: 0:46:21	N	15	15	15	15	15	15	15	8	8	14	12
	Mean	334	5.18	5.72	6.09	6.65	7.03	7.53	166	186	65.5	178.0
	SD	35	0.78	0.59	0.56	0.64	0.72	0.84	16	9	7.3	6.8
Stage 6 Length: 42.8 km Elevation: 310 m Time: 0:51:44	N	19	19	19	19	19	19	19	10	10	18	16
	Mean	330	4.67	4.98	5.53	7.14	8.11	9.11	170	189	71.4	184.1
	SD	54	0.66	0.50	0.32	1.05	1.74	2.27	11	8	4.9	5.5

Note. Watts, absolute power in watts; W/kg, relative power in watt per kg bodyweight; W/kg 20m, relative peak power over 20 min; W/kg 5m, relative peak power over 5 min; W/kg 1m, relative peak power over 1 min; W/kg 30s, relative peak power over 30 s; W/kg 15s, relative peak power over 15 s; HR avg, average heartrate in beats per minute; HR max, maximum heartrate in beats per minute; body mass, rider's body mass in kilogram; height, rider's body height in centimeter; N, sample size; SD, standard deviation.

cubic relationship also applies to mixed-reality competitions. In **Figures 3** and **4**, the relationship between the relative power output (in watts per kg body weight) and the competition result (riding time in milliseconds) is shown in scatterplots for the six stages of the women and men.

Using the example of the relationship between the relative power output and the competition result, the scatterplots of the respective stages show that the cubic graph fits better to the observed data points than the linear or the quadratic graph. Furthermore, comparable cubic patterns can be seen in

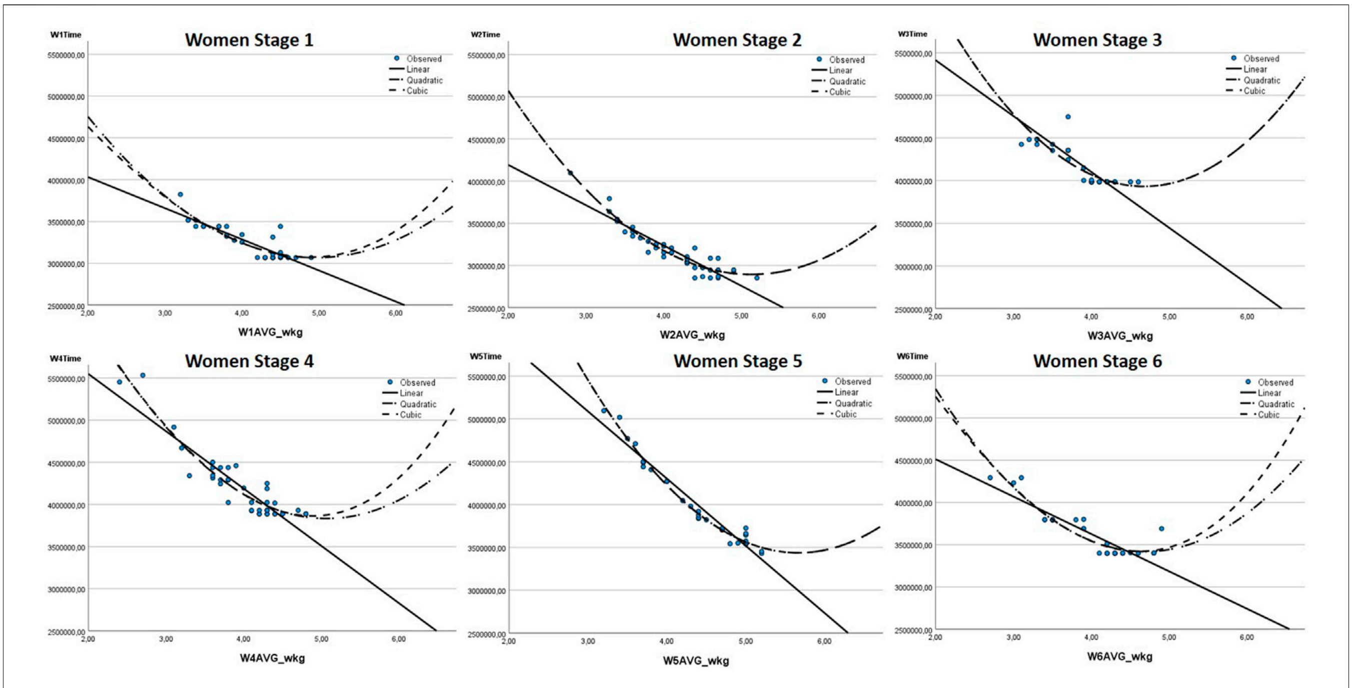

FIGURE 3 | Scatterplot and fitted linear, quadratic and cubic relationship of relative power output (W/kg) and result (riding time in milliseconds) for women's stages.

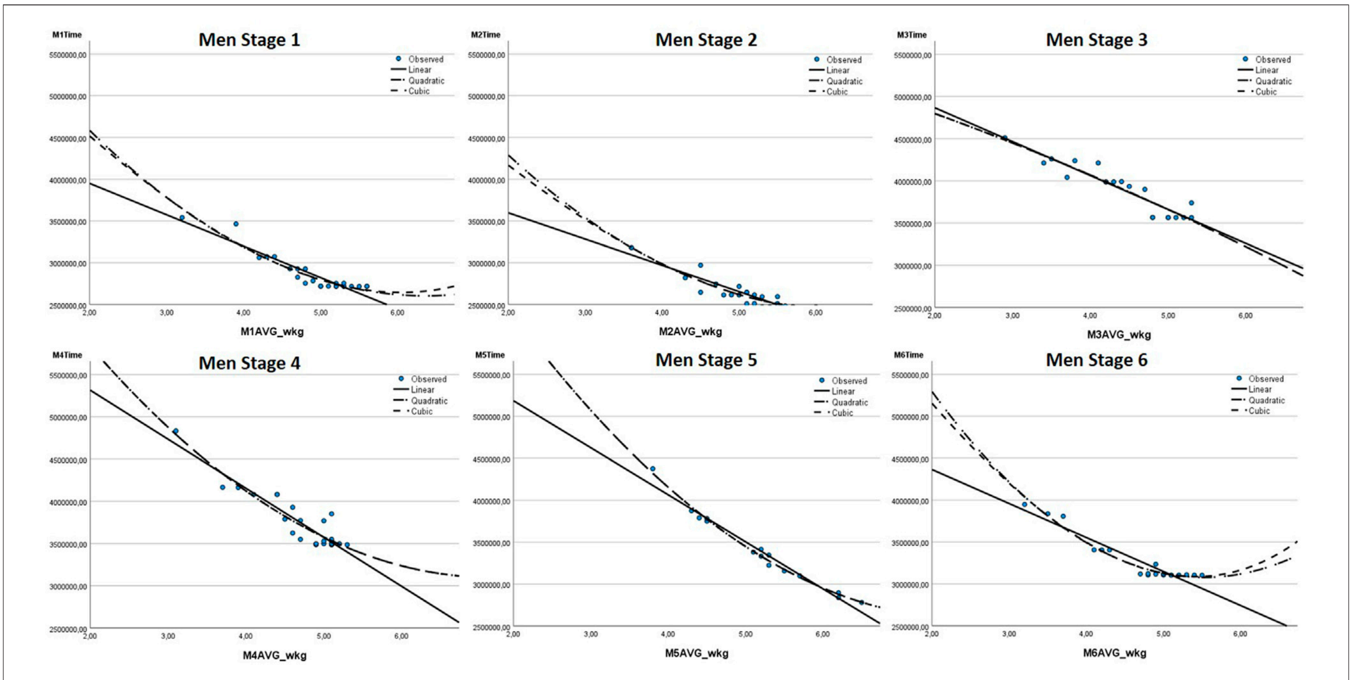

FIGURE 4 | Scatterplot and fitted linear, quadratic and cubic relationship of relative power output (W/kg) and result (riding time in milliseconds) for men's stages.

particular for the other power output parameters (absolute and relative) and in an attenuated form for body mass and height.

Data Analysis

In order to address the research question raised, the influence of the relative and absolute power over the complete duration, the relative power in different time intervals, and the rider's body mass and height on the competition result were analyzed by performing regression analysis. Initially, we selected the appropriate type of regression analysis. Performing multiple regressions based on multiple parameters is not feasible because the variables depend on each other (absolute vs. relative power output) or represent overlapping time intervals. We tested considering multiple parameters. Thereby, the variance inflation factor was above 10 for almost all variables for all stages for both women and men, which is strong evidence for multicollinearity and should therefore be avoided (Hair et al., 2016). For this reason, the regression analyses are performed separately for all parameters that are specified in the research question.

Since the scatterplots in **Figures 3** and **4** indicate a cubic relationship between the parameters and the competition results, third-order polynomial regressions are performed (see **Eq. 1**; Stimson et al., 1978). Polynomial regressions are a type of multiple regression, and therefore the assumptions of 1) no multicollinearity, 2) independence of residuals, 3) homoscedasticity, and 4) normal distribution of residuals must be considered. Multicollinearity often occurs when polynomial regressions are performed, because the first-, second-, and third-order polynomials of the independent variable are usually highly correlated. Therefore, it is not uncommon to have standardized regression coefficients of < −1 or > +1. To attenuate the effects of multicollinearity and improve interpretability of regression results, the included variables were mean-centered before running the polynomial regressions (Dalal and Zickar, 2012). Accordingly, all regressions are based on **Eq. 1**:

$$\boldsymbol{Y} = \boldsymbol{b}_0 + \boldsymbol{b}_1 \times \boldsymbol{x} + \boldsymbol{b}_2 \times \boldsymbol{x}^2 + \boldsymbol{b}_3 \times \boldsymbol{x}^3 + \boldsymbol{e} \qquad (1)$$

In **Eq. 1**, Y is the outcome variable (here: riding time in milliseconds), x is the mean-centered independent variable (predictor; 1) absolute power over the entire distance, 2) relative power over the entire distance, 3) maximum relative power over 20 min, 4) maximum relative power over 5 min, 5) maximum relative power over 30 s, 6) maximum relative power over 15 s, 7) body mass and 8) body height of a rider). b0 is the *Y*-intercept of the regression surface, while b1, b2, and b3 are the estimated coefficients of the predictor's respective polynomial (first-, second-, third-order), and e is the random error component.

While multicollinearity is addressed via the mean centering function prior to running the regression analyses, the other assumptions are tested during the regression analysis to ensure the validity of the results. With regard to the second assumption (the independence of the residuals), the autocorrelation of the residuals is determined by performing the Durbin-Watson test (Allen, 1997). The test statistic values can thereby range from 0 to 4, with 0 indicating a perfectly positive autocorrelation, 4 indicating a perfectly negative autocorrelation, and 2 indicating no autocorrelation. Since the residuals should ideally be independent in polynomial regression, a value of 2 is desirable, while values between 1 and 3 are acceptable (Field, 2013). The third assumption, homoscedasticity of the residuals, is used to verify that the regression model makes good predictions across all values. Therefore, it is checked whether the dispersion of the residuals is constant. Finally, the assumption of normal distribution of the residuals is assessed by histograms. However, potential violations of this assumption have little to no impact on the execution and interpretation of the polynomial regressions (Stimson et al., 1978; Lumley et al., 2002).

All regression analyses were performed on the basis of the data sets described in **Tables 1** and **2** with IBM SPSS Statistics software version 26. The data sets include the performance data of all participants of the respective stage, since the measurement and disclosure of the performance data is a prerequisite for the execution of mixed-reality competitions. To finally obtain the best model fit, the explanatory power of the cubic polynomial regression was compared with the explanatory power of the linear and quadratic functions (Stimson et al., 1978). Compared to the cubic function, neither the linear nor the quadratic regression function achieved a higher overall explanatory power for the relative and absolute performance parameters and body mass and height. Therefore, only the results of the third-order polynomial regression analyses are reported in the following results section.

RESULTS

The results of the third-order polynomial regression analyses for the women's and men's Virtual Tour de France stages are summarized in **Table 3**. Compared to (multiple) linear regressions, polynomial regression analyses do not allow meaningful interpretation of the strength of individual regression coefficients since the polynomials depend on each other and can only be varied simultaneously (Stimson et al., 1978). Accordingly, polynomial regressions are to be evaluated based on global fit indices. The R^2 indicates to what extent the variance of the dependent variable (competition result as riding time on the stage) can be explained by the independent variable (regressor). The *p*-value of the F-statistic indicates the extent to which the calculated R^2 differs significantly from 0. In **Table 3**, regression results are highlighted in italics if they do not meet one or more of the validity criteria. This can happen if 1) the 95% significance level ($p > 0.05$) is not reached, 2) the Durbin-Watson test shows values <1 or >3, which would indicate autocorrelation, or on the basis of the histograms respectively the scatterplots 3) heteroscedasticity or 4) no normal distribution of the residuals is observed. Furthermore, the strongest predictors (largest R^2) for each women's and men's stage are highlighted in bold. All other regression results (non-italics and non-bold) also meet the validity criteria. Due to limited interpretability, standardized regression coefficients, associated *p*-values, regression functions, and confidence intervals are presented in **Supplementary Material SA, SB**. The effects of regressors 1) to 9) on the competition outcome are listed per stage in the same order in **Table 3** as in the research question raised.

The stages of the Virtual Tour de France have varying characteristics. Stage one was held on a hilly course. 1.5 km before the finish, the last mountain classification had to be mastered, followed by a descent to the finish. In the women's race, the results show that relative power output over the entire

TABLE 3 | Regression results of women's and men's stages.

	Regressor	Women			Men		
		F Statistics	R^2	Durbin-Watson	F Statistics	R^2	Durbin-Watson
Stage 1	a) Watts	F(3,29) = 31.927, p < 0.001	0.744	1.543	F(3,20) = 67.618, p < 0.001	0.897	1.189
	b) W/kg	**F(3,29) = 35.774, p < 0.001**	**0.765**	**1.447**	**F(3,20) = 133.695, p < 0.001**	**0.945**	**1.895**
	c) W/kg 20m	F(3,26) = 25.351, p < 0.001	0.716	1.475	F(3,20) = 23.423, p < 0.001	0.745	1.241
	d) W/kg 5m	F(3,29) = 11.666, p < 0.001	0.500	1.078	F(3,20) = 6.050, p = 0.004	0.397	1.035
	e) W/kg 1m	*F(3,29) = 6.703, p = 0.001*	*0.348*	*0.574*	F(3,20) = 8.562, p = 0.001	0.497	1.557
	f) W/kg 30s	*F(3,29) = 6.354, p = 0.002*	*0.334*	*0.630*	F(3,20) = 15.503, p < 0.001	0.654	1.518
	g) W/kg 15s	*F(3,29) = 2.229, p = 0.106*	*0.103*	*0.329*	F(3,20) = 18.867, p < 0.001	0.700	1.717
	h) Body mass	*F(3,25) = 0.505, p = 0.682*	*0*	*0.216*	*F(3,20) = 0.253, p = 0.858*	*0*	*0.210*
	i) Body height	*F(3,24) = 1.177, p = 0.339*	*0.019*	*0.223*	*F(3,16) = 0.479, p = 0.701*	*0*	*0.367*
Stage 2	a) Watts	F(3,37) = 17.584, p < 0.001	0.554	1.309	F(3,21) = 19.444, p < 0.001	0.697	1.170
	b) W/kg	**F(3,37) = 105.864, p < 0.001**	**0.887**	**1.455**	**F(3,21) = 55.731, p < 0.001**	**0.872**	**2.465**
	c) W/kg 20m	F(3,37) = 48.403, p < 0.001	0.780	2.084	F(3,21) = 42.114, p < 0.001	0.837	2.475
	d) W/kg 5m	F(3,37) = 30.094, p < 0.001	0.686	1.738	F(3,21) = 13.689, p < 0.001	0.613	1.726
	e) W/kg 1m	F(3,37) = 18.815, p < 0.001	0.572	1.539	*F(3,21) = 9.307, p <0.001*	*0.509*	*0.966*
	f) W/kg 30s	F(3,37) = 19.434, p < 0.001	0.580	1.503	*F(3,21) = 15.658, p <0.001*	*0.647*	*0.815*
	g) W/kg 15s	F(3,37) = 15.781, p < 0.001	0.526	1.362	F(3,21) = 11.395, p < 0.001	0.565	1.080
	h) Body mass	*F(3,33) = 1.080, p = 0.371*	*0.007*	*0.188*	*F(3,20) = 2.998, p = 0.055*	*0.207*	*0.625*
	i) Body height	*F(3,29) = 3.070, p = 0.043*	*0.241*	*0.441*	*F(3,14) = 0.254, p = 0.857*	*0*	*0.134*
Stage 3	a) Watts	F(3,29) = 50.558, p < 0.001	0.823	1.974	F(3,16) = 16.618, p < 0.001	0.711	1.771
	b) W/kg	**F(3,29) = 67.180, p < 0.001**	**0.861**	**1.727**	**F(3,16) = 35.694, p < 0.001**	**0.846**	**1.612**
	c) W/kg 20m	F(3,25) = 33.765, p < 0.001	0.778	1.819	F(3,14) = 11.213, p = 0.001	0.643	1.283
	d) W/kg 5m	F(3,25) = 8.538, p < 0.001	0.447	1.126	F(3,14) = 9.017, p = 0.001	0.586	1.779
	e) W/kg 1m	F(3,25) = 21.279, p < 0.001	0.685	1.288	F(3,14) = 8.088, p = 0.002	0.556	1.198
	f) W/kg 30s	F(3,25) = 7.835, p = 0.001	0.423	1.171	F(3,14) = 6.773, p = 0.005	0.505	1.198
	g) W/kg 15s	F(3,25) = 5.097, p = 0.001	0.305	1.092	*F(3,14) = 2.550, p = 0.098*	*0.215*	*0.430*
	h) Body mass	*F(3,22) = 0.380, p = 0.768*	*0*	*0.608*	*F(3,15) = 0.746, p = 0.541*	*0*	*0.384*
	i) Body height	*F(3,20) = 1.226, p = 0.326*	*0.029*	*0.337*	*F(3,9) = 0.456, p = 0.720*	*0*	*0.388*
Stage 4	a) Watts	*F(3,33) = 25.102, p <0.001*	*0.668*	*0.995*	F(3,23) = 15.277, p < 0.001	0.622	1.408
	b) W/kg	**F(3,35) = 95.967, p < 0.001**	**0.882**	**1.633**	F(3,23) = 46.446, p < 0.001	0.840	1.533
	c) W/kg 20m	F(3,29) = 26.341, p < 0.001	0.704	1.935	**F(3,19) = 40.354, p < 0.001**	**0.843**	**1.249**
	d) W/kg 5m	F(3,29) = 14.539, p < 0.001	0.559	1.467	F(3,19) = 28.976, p < 0.001	0.792	1.311
	e) W/kg 1m	*F(3,29) = 1.981, p = 0.139*	*0.084*	*0.866*	*F(3,19) = 25.814, p <0.001*	*0.772*	*0.711*
	f) W/kg 30s	*F(3,29) = 2.295, p = 0.099*	*0.108*	*0.790*	F(3,19) = 31.525, p < 0.001	0.806	1.122
	g) W/kg 15s	*F(3,28) = 2.863, p = 0.055*	*0.153*	*0.798*	*F(3,19) = 17.853, p <0.001*	*0.697*	*0.837*
	h) Body mass	*F(3,32) = 0.370, p = 0.775*	*0*	*0.148*	F(3,21) = 5.121, p = 0.008	0.340	1.006
	i) Body height	*F(3,28) = 1.435, p = 0.254*	*0.040*	*0.389*	*F(3,17) = 0.279, p = 0.840*	*0*	*0.201*
Stage 5	a) Watts	F(3,29) = 27.596, p < 0.001	0.714	1.478	F(3,11) = 6.940, p = 0.007	0.560	1.245
	b) W/kg	**F(3,29) = 601.166, p < 0.001**	**0.983**	**1.507**	**F(3,11) = 469.376, p < 0.001**	**0.990**	2.070
	c) W/kg 20m	F(3,29) = 122.040, p < 0.001	0.919	1.792	F(3,11) = 16.755, p < 0.001	0.771	2.353
	d) W/kg 5m	F(3,29) = 31.751, p < 0.001	0.742	1.286	F(3,11) = 16.364, p < 0.001	0.767	2.021
	e) W/kg 1m	F(3,29) = 18.267, p < 0.001	0.618	1.088	F(3,11) = 11.989, p = 0.001	0.702	2.132
	f) W/kg 30s	F(3,29) = 16.346, p < 0.001	0.590	1.192	F(3,11) = 6.909, p = 0.007	0.559	2.115
	g) W/kg 15s	F(3,29) = 13.246, p < 0.001	0.534	1.062	*F(3,11) = 2.834, p = 0.087*	*0.282*	*1.423*
	h) Body mass	*F(3,26) = 0.786, p = 0.512*	*0*	*0.174*	*F(3,10) = 10.102, p = 0.002*	*0.677*	*0.882*
	i) Body height	*F(3,24) = 0.125, p = 0.944*	*0*	*0.070*	*F(3,7) = 2.212, p = 0.174*	*0.267*	*1.128*
Stage 6	a) Watts	F(3,25) = 21.232, p < 0.001	0.684	1.715	F(3,15) = 63.846, p < 0.001	0.913	2.339
	b) W/kg	**F(3,25) =59.397, p < 0.001**	**0.862**	**1.942**	**F(3,15) = 183.748, p < 0.001**	**0.968**	**2.873**
	c) W/kg 20m	*F(3,25) = 9.266, p <0.001*	*0.470*	*0.845*	F(3,15) = 41.259, p < 0.001	0.870	1.246
	d) W/kg 5m	*F(3,25) = 9.307, p <0.001*	*0.471*	*0.889*	*F(3,15) = 4.127, p = 0.026*	*0.343*	*0.925*
	e) W/kg 1m	F(3,25) = 7.308, p = 0.001	0.403	1.365	F(3,15) = 7.709, p = 0.022	0.528	1.164
	f) W/kg 30s	F(3,25) = 5.484, p = 0.005	0.325	1.042	F(3,15) = 4.755, p = 0.016	0.385	1.058
	g) W/kg 15s	*F(3,25) = 1.312, p = 0.293*	*0.032*	*0.308*	*F(3,15) = 4.734, p = 0.016*	*0.384*	*0.944*
	h) Body mass	*F(3,24) = 0.397, p = 0.756*	*0*	*0.208*	*F(3,14) = 0.832, p = 0.498*	*0*	*0.640*
	i) Body height	*F(3,22) = 1.099, p = 0.371*	*0.012*	*0.606*	*F(3,12) = 0.510, p = 0.683*	*0*	*0.526*

Note. W/kg, relative power in watt per kg body weight; Watts, absolute power in watts; W/kg 20m, relative peak power over 20 min; W/kg 5m, relative peak power over 5 min; W/kg 1m, relative peak power over 1 min; W/kg 30s, relative peak power over 30 s; W/kg 15s, relative peak power over 15 s; mass, rider's body mass in kilogram; body height, rider's body height in centimeter; R^2*, coefficient of determination (variance explained); strongest predictor of stage result in bold; results that are not significant at the 5% level are marked in italics.*

stage duration (W/kg) has the greatest influence on the race result (R^2 = 0.765; p < 0.001). Relative power is less important the shorter the time interval considered. In men's race, relative power output over the entire stage (W/kg; R^2 = 0.945; p < 0.001) is also the strongest predictor of success. The relative performances over time intervals of 15 s (W/kg 15s; R^2 = 0.700; p < 0.001) and 30 s (W/kg 30s; R^2 = 0.654; p < 0.001) also still show a high explanatory power.

Stage two led over one high mountain (>500 m of elevation gain) in the middle of the stage and ended with a flat section. In the women's race, the relative performances over the entire distance (W/kg; R^2 = 0.887; p < 0.001) and over 20 (W/kg 20m; R^2 = 0.780; p < 0.001) and 5 min (W/kg 5m; R^2 = 0.686; p < 0.001) are particularly decisive for the race outcome. This result indicates that it was important to get over the mountain in the first group, while in the final part of the race, sprinting skills were less critical as the peloton was split into small groups. The men's race developed in a similar way. Here the relative performance over the entire distance (W/kg; R^2 = 0.872; p < 0.001) also explains most of the success.

Stage three was an undulating course with a slightly hilly finish. In the women's race, the strongest predictor is relative power over the entire distance (W/kg; R^2 = 0.861; p < 0.001). In the men's race, relative power over the entire duration (W/kg; R^2 = 0.846; p < 0.001) is also the strongest predictor.

Stage four led over two smaller and two medium-high mountains (>100 m of elevation gain), with the last medium-high mountain about 3 km from the finish. In the women's race, relative performance over the entire distance (W/kg; R^2 = 0.882; p < 0.001) is the strongest predictor, while shorter time intervals of the relative peak power (<5 min) do not significantly affect the competition result. However, the progression in the men's race was different. Here, a comparatively large group sprinted for the win, which is indicated by the fact that relative peak power over 30 s (W/kg 30s; R^2 = 0.806; p < 0.001) is almost as critical for success as the strongest predictor relative peak power over 20 min (W/kg 20m; R^2 = 0.843; p < 0.001). Notably, body mass (R^2 = 0.340; p = 0.008) significantly affects competition results.

The fifth stage, after a short flat section, led up to a mountain top finish, where a difference in altitude of over 1,000 m had to be overcome. For both women (R^2 = 0.983; p < 0.001) and men (R^2 = 0.990; p < 0.001), relative power output over the entire distance is the strongest predictor of success due to the height of the mountain. For both genders, relative peak power over 1 minute still has a relatively high explanatory power (women: R^2 = 0.618; p < 0.001; men: R^2 = 0.702; p = 0.001). Overall, this is also reflected in the race progressions, which included a few accelerations on the uphill, but it was particularly important to keep relative peak power high to defend the advantage gained all the way to the finish. Remarkably, despite the mountainous course profile, body mass alone has no effect on race performance, neither in women (p = 0.512), nor in men (presence of autocorrelation due to Durbin-Watson statistic <1).

The sixth and final stage followed a slightly hilly route, with the last kilometers being flat. In the women's race, relative peak power over the entire stage (W/kg; R^2 = 0.862; p < 0.001) is the strongest predictor of success and the explanatory power decrease constantly for shorter peak power intervals. In the men's race, a bunch sprint occurred for the win. Here, relative power over the entire stage (W/kg; R^2 = 0.968; p < 0.001) is the strongest predictor for the competition results, while relative peak power interval of 1 minute (W/kg 1m; R^2 = 0.528; p = 0.022) also has a notable impact.

Overall, it appears that relative power output over the entire stage can explain the highest proportion of the variance in the riding time, and thus success in the race, for both women and men. However, the explanatory power (R^2) ranges between 77% and 98% for women and between 84% and 99% for men depending on the stage. Accordingly, for some stages, other performance indicators (regressors) explain success almost as well as - or in individual cases even better than (see men's stage 4) - relative power output over the entire stage, which will be addressed in the following discussion.

DISCUSSION

Previous studies have investigated the relevance of absolute and relative power output (Gallo et al., 2021; Lee et al., 2002) and peak power (Faria et al., 2005) for success by relating performance data measured in a laboratory setting to success in outdoor competitions that are not directly related to that data. This study advances such work by focusing on mixed-reality sports platforms to analyze performance data from competition in combination with the directly corresponding competition outcome. Following the relationship between the power output generated by a rider and the resulting speed in the real world, a cubic relationship was assumed for the regression analyses performed here to model the relationship between the performance data and the riding time of the avatar over a defined distance in the virtual world. The third-order polynomial regression analyses reveal that the assumed cubic relationship also applies to mixed-reality sports.

We contribute to sports physiology science by indicating that the (relative) in-competition power output is the strongest predictor of success in mixed-reality competitions. The explanatory power of the examined power output, body mass, and body height depends on the course characteristics and the progression of the race. The role of course characteristics is indicated by the fact that for flat stages, the explanatory power of absolute and relative power output over the entire duration are comparable (e.g., stage 1 women: R^2watts = 0.744 vs. R^2w/kg = 0.765; stage 1 men: R^2watts = 0.897 vs. R^2w/kg = 0.945; similar effects are observed for stages 3 and 6). For mountain stages, the explanatory power of relative power output over the entire distance is considerably higher than for absolute power output (e.g., stage 5 women: R^2watts = 0.714 vs. R^2w/kg = 0.983; stage 5 men: R^2watts = 0.560 vs. R^2w/kg = 0.990; similarly, for stage 4). Body mass alone is a significant predictor of athletic success only on the mountain stages (e.g., stage 4 men: R^2body mass = 0.340). The effect of the progression of the race on the relevance of different performance parameters for the competition's result can be seen in the fact that on identical courses in the women's and men's races, different performance parameters explained success substantially differently. For example, stage 1 of the women's race was ridden offensively, and the winner was decided in the sprint of a leading group. This shows that the relative performance over the entire distance has the strongest explanatory power (R^2w/kg = 0.765) and decreases with the observation of shorter time intervals (e.g., R^2w/kg 5m = 0.500), since it is initially critical for success to be in the leading group. Stage 1 of the men was decided in a mass sprint. Here, the relative power over the entire distance (R^2w/kg = 0.945) also has the highest explanatory power, which initially also decreases with shorter time intervals of the relative peak power (e.g., R^2w/kg 5m = 0.397), but then increases again substantially for the shortest time intervals considered (R^2w/kg 30s = 0.654; R^2w/kg 15s = 0.700), which might represent the critical performance in the mass sprint. Body height cannot explain the success in any stage. This result is notable because participants are required to report their height and current body mass prior to the competition. Furthermore, the scatterplots and the polynomial regressions showed that in mixed-reality competitions, there is a cubic relationship between power output and speed (riding time over a defined distance). The cubic relationship is also present in the real world, where aerodynamic drag is especially important at high speeds, in addition to gravity and rolling resistance (Kyle, 2003). Although the body height of the athletes is considered in mixed-reality competitions, we could not observe a significant influence on the competition result. The frontal area of the bike on which the power output is performed on the smart trainer in the real world has no effect on the competition result. The reason for this is that the athletes cannot provide any information on this before the competition, and therefore it cannot be taken into account by the algorithms of the mixed-reality sports platform. In summary, on the one hand, relative power over a long period of time is especially critical for success when long mountains have to be overcome on the course or when the race is ridden very offensively, and the peloton is divided into many small groups of riders. On the other hand, relative peak power over a shorter period of time is increasingly relevant with shorter climbs, especially towards the end of the race or when the race is decided in a bunch sprint.

We can conclude that the power profile of a mixed-reality cycling race is more complex compared to the rather constant power profiles that are delivered during ergometer tests in a laboratory setting over a specific period of time (e.g., 30 min; Lee et al., 2002) or in a time trial (e.g., Padilla et al., 2000). Understanding the power profile and its effect on competition outcome allows the transfer of insights from studies. Internal factors such as specific training programs or altitude training can be used to improve athletes' critical performance parameters (e.g., Jeukendrup and Martin, 2001). In addition, factors such as seating position (Hansen and Waldeland, 2008), gear ratio and pedaling cadence that affect the cycling economy (Faria et al., 2005), or nutritional strategy (Atkinson et al., 2003) may increase relevant performance in mixed-reality competition. The findings from the area of indoor cycling are also relevant, where in particular an effect of starting strategy (Mattern et al., 2001), time of day (Atkinson et al., 2005), warm-up (Munro et al., 2017), recovery duration (Glaister et al., 2005), and precooling strategy (Quod et al., 2008) on athletic performance has been proven. It has already been demonstrated that the starting strategy in mixed-reality races is considerably different from that in road races, as the effort at the beginning of the race is significantly higher in mixed-reality races (Westmattelmann et al., 2021a).

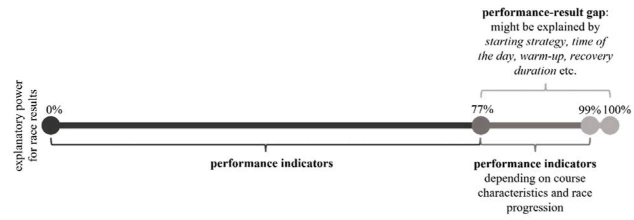

FIGURE 5 | Performance-result gap exemplified by the Virtual Tour de France 2020.

This study revealed that specific performance parameters (power output) are the main predictors of success in mixed-reality competitions. Nevertheless, success in any stage of the Virtual Tour de France could not be explained entirely by only one of the performance parameters, resulting in a performance-result gap, which varies in size between 1% and 23% (**Figure 5**), depending on the characteristics of the course and the progression of the race. At first, it might be relevant at which point in time during the race the athletes produce certain power outputs. For example, a higher power output towards the end of the race or on a mountain could be more critical for success than if the power is produced at the beginning of the race or on a downhill segment. Furthermore, different external parameters could also explain the performance-result gap. Weight and aerodynamics of the real-world bike and the rider's position are not directly relevant because the rider produces the performance while stationary on a smart trainer. In contrast, as aerodynamics, including slipstream effects, are simulated, and different virtual bikes and corresponding equipment have different weight and aerodynamic characteristics that resemble the real-world equipment, these can affect the competition result. Simulated slipstream effects, team strategy, or positioning in the peloton might also explain the performance-result gap (Van Erp et al., 2021b). It has to be mentioned that the rider's positioning in the virtual race depends mostly on the rider's power output because steering skills are not considered. Still, due to the absence of consideration of steering skills in mixed-reality competitions, such skills are likely to be less relevant for the competition result than in road races. While mechanical failures can be critical in road races, the risk of mechanical failures is much lower in mixed-reality competitions. For example, while the chain can still break, a punctured tire has no impact on the race. However, technical failures in the form of an unstable internet connection or crashed software are potential race-deciding aspects in mixed-reality competitions (Lazzari et al., 2020). Finally, the performance-result gap can also be explained by specific knowledge about the mixed-reality sports platform. A corresponding example from the Zwift platform represents the effective use of power-ups, which make the athlete lighter, more aerodynamic, or invisible to competitors for a certain period of time and can thus be crucial for the race result (Westmattelmann et al., 2021a).

Practical Implications

Based on our findings, recommendations for action can be offered to different stakeholder groups in sports. First, our results provide athletes and coaches insights into which performance parameters are critical for success in mixed-reality sports. Accordingly, training programs can be tailored to prepare athletes to deliver the relevant critical performances. Since we provide extensive knowledge on the performance profile of mixed-reality competitions, they can also be systematically integrated into the preparation for real-world competitions to train in a competition-specific manner. This is especially beneficial when no competitions occur in the off-season, when factors such as unfavorable weather at outdoor competitions pose an increased risk of injury or infection.

Our analysis offers coaches, sports directors, or team managers a solid basis for decision-making to deploy athletes in mixed-reality competitions according to the respective course characteristics. For example, performance data from training or performance diagnostics can be compared with the required performance profiles of mixed-reality competitions. This allows the selection of athletes whose performance best matches the required performance profile. Furthermore, due to the wide availability of performance data, mixed-reality competitions offer scouts the opportunity to track and recruit athletes based on their performance and body composition.

For mixed-reality sports platform operators, it is valuable to show that physical performance is the most critical factor for success in the competitions on their platform. Accordingly, mixed-reality sports competitions host relevant and authentic athletic performances, which underlines the relevance of mixed-reality events. It is also notable that success is not solely determined by physical performance in mixed-reality competitions. This uncertainty about the outcome of the competition makes mixed-reality competitions interesting for spectators.

Finally, we provide key insights for sports federations on how to deal with mixed-reality sports platforms. Mixed-reality-specific factors might explain the performance-result gap, which raises the question for sports federations as to the extent to which they want to establish mixed-reality competitions as an independent discipline. In this regard, federations need to decide whether the mixed-reality events should be as realistic as possible or whether they deliberately enhance the presence of gamified elements and mechanisms. While discipline-specific skills and strategies are relevant in traditional cycling disciplines such as road cycling, mountain-biking, cyclo-cross, or track racing, the same is true for mixed-reality cycling. Mixed-reality cycling has the potential to introduce people with an affinity for esports to traditional sports and thus represents a promising extension to appeal to a younger target group. At the same time, it will be interesting to observe whether professionals from road cycling will also participate in mixed-reality cycling competitions in the future, as in the Virtual Tour de France, 2020b, or whether a separate professional scene will emerge.

Limitations and Further Research

There are potential limitations to this study. First, the stages of the Virtual Tour de France were conducted in a decentralized manner due to the Covid-19 pandemic, so the organizers could not monitor the calibration of the smart trainer or the body mass and height of the riders to the same extent as that would have been the case if the event had been conducted in a centralized manner. In their analysis of the Virtual Tour de France, Westmattelmann et al. (2021b) showed that the performance data correspond to the performances of real-world professional races but also observes suspicious weight data. However, since minor differences in performance can be decisive for victory and defeat in competitive sports, the reliability of the measured data needs to be considered further so that, for example, incorrect calibrations of the smart trainer or power meter can be identified.

Second, the ability to apply the insights gained here from mixed-reality cycling races to road races might be limited. First, the competition mode differs, as the Virtual Tour de France, 2020b featured a team competition, which could affect the team strategy. In contrast, the Tour de France is decided based on the total riding time in an individual classification. In addition, in the Virtual Tour de France, 2020b, riders were swapped between stages, and the starting fields were also much smaller than in the real-world Tour de France. Nevertheless, the athlete population considered in this study is representative of the real-world Tour de France as the men's Virtual Tour de France included almost exclusively professional teams and riders who also compete in the real Tour de France, while the women's Virtual Tour de France included professionals.

Although essential aspects from the real world were simulated in the Virtual Tour de France such as elevation profiles and slipstream effect, there are still differences, such as power-ups or the non-inclusion of steering skills, as the avatar steers autonomously. Furthermore, some environmental factors, such as rain or crosswinds, which can affect the race result in road races, are not considered in mixed-reality races. Follow-up studies should aim to investigate the extent to which gamification elements such as power-ups are used strategically by riders and what effect the power-up use has on competition outcomes and thus explain the performance-result gap. In view of the increasing importance of mixed-reality sports, the results presented here nevertheless show a high relevance for sports physiology science (see Crivoi do Carmo et al., 2022). The wide-ranging data transparency required to conduct mixed-reality sport goes far beyond the data available from traditional sport and thus offers plenty of new research opportunities. Since the power output data of all participants of the Virtual Tour de France are available and were considered in this study, the effect of race performance data on the competition result can be quantified for the first time.

CONCLUSION

This study shows that success in mixed-reality sports particularly depends on athletes' physical performance. Exemplified by the performance data, rider's body mass and height as well as results of the Virtual Tour de France, we demonstrate that the relative power output over the entire stage distance explains most of the variance in the riding time. However, depending on the course characteristics and the race progression, the explanatory power of the considered performance indicators differs in some cases considerably. While relative peak performances over a long period are most critical for success in races with longer climbs, relative peak performances of around 1 minute are critical for success in flatter races ending in a bunch sprint. The relevance of the relative performance indicates that the body mass of the riders has some importance. However, body mass alone can predict race success only occasionally when a mountain lies just before the finish. There was no significant effect for body height on the race result observed.

Overall, insights from sports science can be applied to train specific critical performances (e.g., Jeukendrup and Martin, 2001). Although physical performance is the main predictor of success in mixed-reality sport, a performance-result gap is identified. Depending on the stage, a maximum of 77%–98% of success in women and 84%–99% in men could be explained by performance indicators. Future studies will have to quantify which additional factors can explain this gap. Due to the complete availability of in-competition performance data, mixed-reality offers new research opportunities for sports science. Furthermore, mixed-reality sport has the potential to attract new audiences as an individual discipline and to complement traditional sport.

DATA AVAILABILITY STATEMENT

The datasets analyzed for this study will be made available by the authors upon request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the School of Business and Economics of the University of Münster, Germany. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

DW: Conceptualization, methodology, analysis, writing, project administration. BS: Conceptualization, writing, visualization. MS: Methodology, writing. J-GG: Conceptualization, writing. GS: Supervision, writing.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2022.868902/full#supplementary-material

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Greater Breast Support Is Associated With Reduced Oxygen Consumption and Greater Running Economy During a Treadmill Running Task

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Introduction: Breast pain is a major barrier to running for women. While breast support through the use of sports bras reduces breast-related discomfort, the effect of breast support on running performance is less understood. Therefore, the purpose of the current study was to evaluate the effect of greater breast support on oxygen consumption and running economy during a treadmill running task.

Methods: Fifteen female recreational runners performed a 10-min treadmill running task at their preferred running speed in each of two sports bra conditions: low support and high support. Participants ran on an instrumented treadmill (1,200 Hz, Bertec) while indirect calorimetry was performed using a metabolic measurement system (100 Hz, TrueOne, ParvoMedics). Average VO_2 (absolute and relative) from the third to 10th minutes was used to evaluate oxygen consumption. Running economy was calculated as the distance traveled per liter of oxygen consumed. Paired samples *t*-tests were used to compare mean oxygen consumption and running economy values between breast support conditions. Correlation analysis was performed to evaluate the relationship between breast size and change in running performance.

Results: Greater breast support was associated with reductions in absolute ($p < 0.001$) and relative oxygen consumption ($p < 0.001$; LOW: 30.9 ± 7.1 ml/kg/min; HIGH: 28.7 ± 6.7 ml/kg/min). Greater breast support was associated with increases in running economy ($p < 0.001$; LOW: 88.6 ± 29.1 m/L O_2; HIGH: 95.2 ± 31.1 m/L O_2). No changes in temporospatial characteristics of running were observed including cadence ($p = 0.149$), step length ($p = 0.300$) or ground contact time ($p = 0.151$). Strong positive linear correlations were observed between the change in running performance metrics and breast size (Oxygen Consumption: $p < 0.001$, $r = 0.770$; Relative Oxygen Consumption: $p < 0.001$, $r = 0769$; Running Economy: $p < 0.001$, $r = 0.807$).

Conclusions: Greater breast support was associated with reduced oxygen consumption and increased running economy. These findings demonstrate that greater breast support is not only associated with improved comfort but also improved running performance.

Keywords: running, treadmill, bioenergetics, VO_2, oxygen consumption, running economy, breast, sports bra

INTRODUCTION

Running is a popular form of physical activity that has been shown to benefit cardiovascular and musculoskeletal health (Williams et al., 1984; Piacentini et al., 2013; Lavie et al., 2015; Kozlovskaia et al., 2019). For many women, however, breast pain is a significant barrier to exercise including running-based activities (Scurr et al., 2011a; Risius et al., 2017; Brisbine et al., 2020; McGhee and Steele, 2020b). It is reported that up to 72% of females experience breast pain during exercise-related activities (Gehlsen and Albohm, 1980; Bowles et al., 2008; Scurr et al., 2010). Several factors are suggested to underlie exercise-induced breast pain including large breast displacements as well as high breast velocities and accelerations (McGhee and Steele, 2020a). Moreover, these breast displacement magnitudes are influenced by breast size with larger breasts experiencing greater breast displacement magnitudes compared to smaller breasts (McGhee and Steele, 2010a; McGhee et al., 2013). For example, females with a D-cup breast size can experience vertical breast displacements as high as 20 cm when running without breast support (McGhee et al., 2007; Scurr et al., 2011a). However, when external breast support was provided in the form of a sports bra, vertical breast displacements decreased (Scurr et al., 2011a,b; Risius et al., 2017), attenuating perceived breast pain and improving breast comfort (Scurr et al., 2011b; Milligan et al., 2015; Risius et al., 2017; McGhee and Steele, 2020b).

Breast excursion velocity is another factor that contributes to breast discomfort and breast pain. During running, the breasts experience high magnitudes of excursion velocity in the downward direction (McGhee et al., 2007; Scurr et al., 2009; McGhee and Steele, 2020a) which are purported to be the primary cause of breast pain and discomfort during running. These high vertical breast excursion velocities are created by the difference in timing between the vertical motion of the trunk and breasts. As the trunk decelerates following initial contact, the breasts continue their downward progression at a greater rate than the trunk resulting in the breasts forcefully contacting the anterior trunk wall (McGhee et al., 2007; Scurr et al., 2009; McGhee and Steele, 2020a). A study by McGhee et al. (2007) revealed that females with a C-cup breast size or greater experienced peak breast velocities of 80 cm/s in the upward direction and 100 cm/s in the downward direction during treadmill running. However, when breast velocities were reduced by performing deep water running, running-related breast pain was reduced (McGhee et al., 2007). Due to the greater breast displacement magnitudes associated with larger breast sizes, breast excursion velocities are also proposed to be greater in women with larger breasts (McGhee and Steele, 2010a; McGhee et al., 2013). Therefore, interventions reducing breast displacements and the resultant breast excursion velocities should disproportionately reduce breast pain in individuals with larger breasts.

Greater breast support also alters trunk and pelvis biomechanics during treadmill running. During running, transverse plane rotations of the trunk and pelvis act to balance rotational momentum about the body's center of mass while pelvis rotation is an important contributor to step length and subsequently cadence (Preece et al., 2016). However, Milligan et al. (2015) reported that greater breast support was associated with increased transverse plane trunk and pelvis excursions during treadmill running. Further, greater breast support was associated with increased vertical oscillations of the trunk and pelvis (Risius et al., 2017). These support-related changes in running biomechanics are indicative of a less constrained neuromuscular system, believed to be the result of reduced breast excursions and excursion velocities associated with greater breast support (Milligan et al., 2015; Risius et al., 2015, 2017). A potentially important change in running biomechanics with increasing levels of breast support relates to changes in the vertical oscillations of the trunk and pelvis which may be indicative of altered metabolic cost of running.

The influence of breast support on the bioenergetics of running have not been well established. Only a single study has directly investigated the effect of increasing levels of breast support on the metabolic cost of treadmill running (Risius et al., 2017) and reported no significant changes in variables associated with running bioenergetics including heart rate, oxygen consumption, running economy, minute ventilation or breathing frequency. However, this study had a relatively small sample size of 10 participants with an unreported level of running experience. The effect of breast support on metabolic cost and running economy in female recreational runners remains unknown. Therefore, the purpose of this study is to directly investigate the effect of increasing levels of breast support on oxygen consumption and running economy during a steady-state treadmill running task. It was hypothesized that greater breast support would be associated with reduced oxygen consumption and increased running economy. Further, it was hypothesized that changes in oxygen consumption and running economy would be influenced by breast size.

MATERIALS AND METHODS

Participants

An *a priori* power analysis (G*Power 3.1.5) was conducted based on preliminary data of oxygen cost during running in the high-compared to low-support sports bra. Using an effect size of 0.5, an alpha level of 0.05 and power (1-β) of 0.80, a sample size of 15 participants was determined to provide sufficient statistical power for this study. A total of 15 female recreational runners were recruited to participate in the current study. Participants were included if they were: (1) 18–30 years of age, (2) recreational runners with a running mileage >12 miles per week, (3) had a self-reported bra size of B-cup to DD-cup, (4) had no history of prior breast surgeries (augmentation or reduction), (5) had no recent history of lower extremity injury that would negatively affect their running performance (6 months) and (6) were free of injury at the time of testing. All participants had a multi-year history of endurance running with similar or greater running volume than the listed inclusion criteria. The experimental protocol (PRO-FY2020-431) was approved by the University of Memphis Institutional Review Board and all participants provided written informed consent prior to data collection.

Experimental Protocol

Age and anthropometric measurements including height (m), mass (kg), and bust and underbust circumferences (cm) and were acquired prior to the running protocol. Each participant's breast size was determined based on the difference between their bust and underbust circumferences (McGhee and Steele, 2010b). One cup size was defined as a one inch (2.54 cm) difference between the bust and underbust circumferences (McGhee and Steele, 2010b). For example, a B-cup was defined as a 2-inch (5.08 cm) bust-underbust difference while a DD-cup was defined as a 5-inch (12.7 cm) bust-underbust difference. Bust and underbust circumferences were measured using a standard retractable measuring tape (ERT-963, Elite Medical Instruments, Orange County, California, USA) while the participant was wearing the low support sports bra provided by researchers. Participants were then provided with the designated size sports bras based on the manufacturer's suggested sizing. Participants verbally confirmed the fit of the sports bra as well as their comfort in the sports bra size. The LOW conditions required the participant to wear a sports bra that is described by the manufacturer as having "light" support for low-impact workouts. The low support sports bras offered the breasts limited support. The low support sports bra was the Nike Dri-FIT Indy (Nike Inc., Beaverton, OR, USA). The sports bra included padding inserts; however, the participants were asked to remove the padding inserts from the sports bra prior to testing. The fabric of the sports bra includes a body and lining made of 88 percent recycled polyester and 12 percent spandex, center back mesh and bottom hem made of 81 percent nylon and 19 percent spandex, elastic made 84–85 percent nylon and 15–16 percent spandex, interlining made of 80 percent polyester and 20 percent spandex, pad top fabric and pad back fabric made of 100 percent polyester, and pad made of 100 percent polyurethane. The HIGH condition required the participant to wear a sports bra that is described by the manufacturer has having their "highest" level of support with a compressive feel for minimal bounce. The high support sports bra was the Nike Dri-FIT Alpha (Nike Inc., Beaverton, OR, USA). The sports bra included both adjustable straps and padding. The fabric of the sports bra includes a body and back lining insets made of 79 percent nylon and 21 percent spandex, mesh and mesh lining made of 81 percent nylon and 19 percent spandex, pad made of 100-polyurethane, and pad back fabric made of 100 percent polyester. **Figure 1** demonstrates the differences in support offered by the Nike Indy and Alpha sports bras for a female participant with a breast size of 15.0 cm. Sports bra sizing was completed for both sports bras prior to the beginning of the dynamic testing protocol. The order of presentation of sports bra conditions was randomized between the HIGH and LOW support sports bras.

Prior to dynamic testing, all participants performed a 10-min warm up that consisted of stationary cycling, stretching and light running. Each participant's preferred running speed was then measured over a 20 m runway using an electronic timer and two photocells (63501 IR, Lafayette Instruments Inc., IN, USA). The participant was instructed to run at a pace they would feel comfortable for a "normal" 30-min training run while their running speed was measured over a 3 m distance in the middle of the 20 m runway. The participant's running velocity was used for both experimental conditions.

Following completion of the warmup and determining the participant's preferred running speed, participants were fitted to the metabolic measurement system (TrueOne, ParvoMedics, Salt Lake City, Utah, USA). Each participant was placed in a mask that covered their mouth and nose (Hans Rudolph) which was connected to the metabolic measurement system via a plastic tube (**Figure 2**). The mask was held in place by a series of plastic straps that wrapped around the posterior and superior aspects of the participant's head and were closed via Velcro closures. Prior to initiating dynamic testing, proper fit of the mask on the participant's face was checked by research staff. Proper mask fit was characterized by no air escaping around the sides of the mask when the participant expired air forcefully.

Once the participant had been fitted for the metabolic measurement system, they completed a 10-min treadmill running trial in each of two randomized breast support conditions: LOW and HIGH. During the running trial, oxygen consumption was measured by the metabolic measurement system while temporospatial characteristics were determined from ground reaction force (GRF) data collected using an instrumented treadmill (1200 Hz, Bertec, Split Belt, Columbus, Ohio, USA). The two 10-min running trials were separated by a 10-min period of rest in which the participant was removed from the metabolic measurement system. Following the completion of the 10-min rest period, the experimental protocol was repeated in the other breast support condition.

Data Analysis

Oxygen consumption (in L/min) for each participant in each condition was represented by the average oxygen consumption between the third and 10th minutes. Oxygen consumption from the first 2 min of each treadmill running trial was discarded as the participant was not considered to be in steady state over this period (Whipp et al., 1982). Relative oxygen consumption for each participant in each condition was calculated as the average oxygen consumption in mL divided by the participant's body mass in kg (ml O_2/kg/min). Running economy (in m/L O_2) was calculated as the participant's (treadmill) running velocity (m/s) multiplied by 60 then divided by their oxygen consumption (L/min).

Each participant's cadence, step length and ground contact time were determined from GRF data. GRF data were filtered using a fourth-order, zero-lag Butterworth filter with a 40 Hz cutoff frequency. Initial contact (IC) was defined as the instant in which the vertical GRF signal exceeded a threshold of 50 N for a period >33 ms. Toe off (TO) was defined as the instant at which the vertical GRF decreased below a threshold of 50 N for a period >33 ms. Cadence (in steps/min) was calculated as the total number of ICs (right and left) completed during the recording period divided by the duration of the recording period in minutes (7 min). Step length (in m) was calculated as the time (in seconds)

FIGURE 1 | Anterior, posterior and lateral views of a participant with D-Cup sized breasts in the high support Nike Alpha **(A–C)** and low support Nike Indy **(D–F)**. The athlete was classified as a D-Cup based on the difference between her bust and underbust circumferences (Bust: 84 cm; Underbust: 73.5 cm; Difference: 10.5 cm). The high support sports bra is designed to lift and compress the breast tissue while the low support sports bra is not designed with these features.

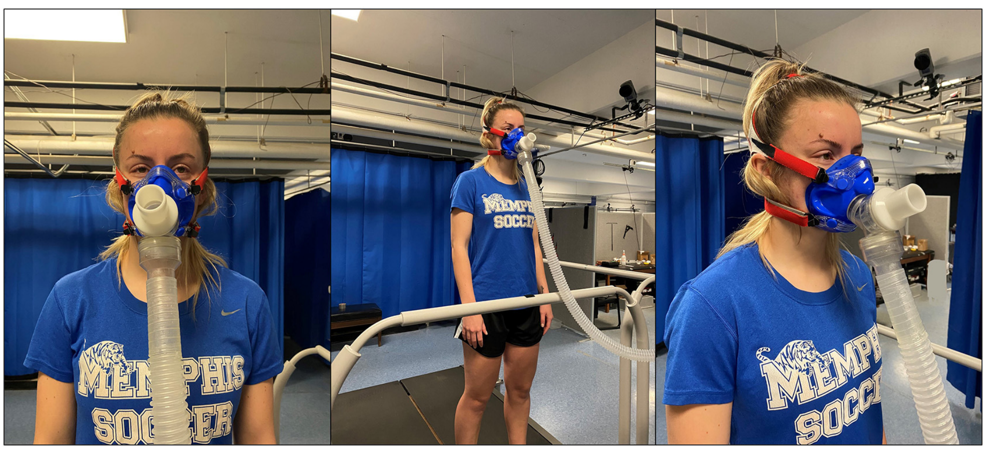

FIGURE 2 | Anterior and anterolateral views of the ParvoMedics TrueOne metabolic measurement system. Expired gases were collected from the participant via a face mask and plastic hose. A proper seal around the mouth and nose was confirmed by research staff prior to testing.

between subsequent ICs (right then left, etc.) multiplied by the treadmill running speed (m/s). Ground contact time (GCT) was calculated as the time (in ms) between the events of IC and TO for the left and right limbs.

Statistical Analysis

Prior to statistical testing, normality of data for each dependent variable were assessed using a Shapiro-Wilks test. In the presence of a significant Shapiro-Wilks test, non-parametric tests of differences and relationship were used, otherwise, parametric testing was implemented. Parametric tests of differences and relationship included paired samples t-tests and Pearson-Product Correlation Coefficients. Non-parametric tests of difference and relationship included Wilcoxon Matched-Pairs Signed Rank test and Spearman Rank Correlations.

Tests of differences were used to compare mean (or median) values for each dependent variable in the HIGH compared to LOW conditions including oxygen consumption, running economy and temporospatial characteristics. Cohen's d estimates of effect size were used to evaluate the effect of breast support on oxygen consumption, running economy and temporospatial characteristics (Cohen, 1988). Effect sizes were interpreted as follows: trivial, $d < 0.02$, small, $0.2 < d < 0.5$, moderate; $0.5 < d < 0.8$; large, $0.8 < d$.

The relationships between breast size and breast support-related changes in performance were quantified using Pearson Product correlation coefficients (r) or Spearman Rank correlation coefficients (ρ). Coefficients of determination (r^2) were used to evaluate the proportion of variation in performance explained by greater breast support. Statistical analyses were conducted using Prism 9.0 (GraphPad Software, San Diego, CA). Significance was set at $p < 0.05$.

RESULTS

Participants

Table 1 presents participant information including age, height, mass, breast size and preferred running speed for each participant. Participants had an average age of 22.0 ($\pm$2.3) years, average height of 1.65 ($\pm$4.4) m, average mass of 68.1 ($\pm$9.7) kg, average breast size of 11.7 ($\pm$2.4) cm and an average running speed of 2.9 ($\pm$0.4) m/s.

Oxygen Consumption

Table 2 presents oxygen consumption data for each participant during the treadmill running task. The HIGH compared to LOW support condition was associated with reductions in absolute oxygen consumption measured as the average volume of Oxygen consumed (**Figure 3A**, $p < 0.001$, $t = 5.79$, $d = 0.39$). When normalized to body mass (ml/kg/min), relative oxygen consumption was also lower in the HIGH compared to LOW support condition (**Figure 3B**, $p < 0.001$, $t = 5.83$, $d = 0.32$).

Figures 4A,B present the relationship between breast size (in cm) and reductions in (A) absolute and (B) relative oxygen consumption during the treadmill running task. A significant positive correlation was observed between breast size and reductions in absolute oxygen consumption in the HIGH compared to LOW support condition ($p < 0.001$, $r = 0.770$, $r^2 = 0.592$). A similar significant positive correlation was observed between breast size and reductions in relative oxygen consumption in the HIGH compared to LOW support condition ($p < 0.001$, $r = 0.769$, $r^2 = 0.591$).

Running Economy

Table 3 presents running economy values for each participant. The Wilcoxon test revealed greater running economy in the HIGH compared to LOW support condition (**Figure 5**, $p < 0.001$, Median $= 6.20$, $d = 0.22$). Further a significant positive

TABLE 1 | Individual participant anthropometric data including age, height, mass, breast size and cup size.

Subject	Age (years)	Height (m)	Mass (kg)	Breast size (cm)	Cup size	Speed (m/s)
S1	21	1.67	77.4	15.0	DD	2.6
S2	21	1.69	81.8	12.0	D	2.5
S3	20	1.66	74	9.5	C	2.9
S4	20	1.60	82.4	12.0	D	2.5
S5	27	1.66	68.3	12.5	D	2.7
S6	22	1.62	54.2	13.5	DD	2.5
S7	21	1.70	60.5	14.5	DD	3.5
S8	21	1.64	53.2	10.7	C	3.1
S9	20	1.63	65	12.0	D	3.3
S10	20	1.61	65.5	12.0	D	3.2
S11	24	1.78	76.1	13.5	DD	3.2
S12	24	1.65	77.3	14.0	DD	3.4
S13	26	1.67	57.5	9.0	C	2.8
S14	23	1.63	61.5	7.1	B	3.3
S15	20	1.66	66.3	8.0	C	2.1
Mean	22.0	1.66	68.1	11.7		2.9
SD	2.3	0.04	9.7	2.4		0.4

Breast size was calculated as the difference between bust and underbust circumferences. Each participant's preferred running speed is also presented.

TABLE 2 | Absolute and relative oxygen consumption values as well as relative change in oxygen consumption in the HIGH compared to LOW support conditions are presented.

Subject	Breast Size (cm)	LOW (VO_2 L/min)	HIGH (L VO_2 (/min)	% Change	LOW	HIGH	% Change
S1	15.0	2.27	1.97	13.4	29.4	25.4	13.4
S2	12.0	2.16	2.03	6.0	26.4	24.9	6.0
S3	9.5	1.63	1.58	2.6	22.0	21.4	2.6
S4	12.0	2.44	2.31	5.3	29.6	28.0	5.3
S5	21.5	2.53	2.15	15.0	37.0	31.5	15.0
S6	13.5	1.79	1.66	7.2	33.1	30.7	7.2
S7	14.5	2.09	1.88	10.2	34.6	31.0	10.2
S8	10.7	2.15	1.96	8.8	40.4	36.8	8.8
S9	12.0	1.88	1.79	4.7	29.0	27.6	4.7
S10	12.0	1.10	1.02	7.2	16.8	15.6	7.2
S11	13.5	2.58	2.38	7.7	33.9	31.3	7.7
S12	14.0	2.04	1.86	8.7	26.4	24.1	8.7
S13	9.0	2.61	2.55	2.3	45.4	44.3	2.3
S14	7.1	1.98	1.95	1.7	32.2	31.7	1.7
S15	8.0	1.81	1.76	2.7	27.4	26.6	2.7
Mean	12.3	2.07	1.92*	6.9	30.9	28.7*	6.9
SD	3.5	0.40	0.36	4.0	7.1	6.7	4.0

The HIGH compared to LOW support sports bra was associated with reduced absolute ($p < 0.001$, $t = 5.79$) and relative oxygen consumption ($p < 0.001$, $t = 5.83$).
*Note: * - denotes a significant difference compared to the LOW condition.*

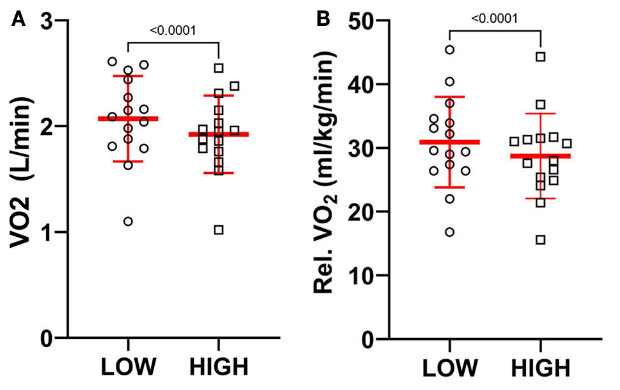

FIGURE 3 | A comparison of individual and mean **(A)** absolute and **(B)** relative oxygen consumption in the LOW and HIGH support conditions during the treadmill running task. A significant reduction in oxygen consumption was observed in the HIGH compared to LOW support conditions.

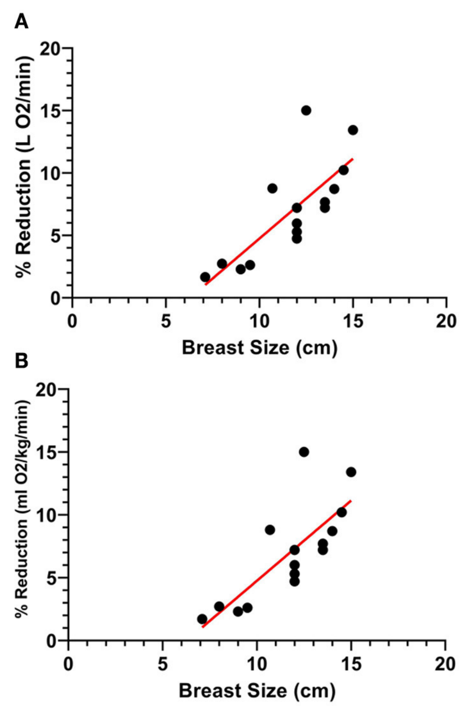

FIGURE 4 | A strong, significant positive relationship was observed between participant breast size (cm) and breast support-induced reductions in **(A)** absolute and **(B)** relative oxygen consumption during the treadmill running task.

correlation was observed between the increase in running economy in the HIGH compared to LOW support condition and participant breast size (**Figure 6**, $p < 0.001$, $\rho = 0.807$, $\rho^2 = 0.651$).

Temporospatial Characteristics of Running

Table 4 presents temporospatial characteristics of the two treadmill running conditions including cadence, ground contact time, and step length. No differences were observed in cadence ($p = 0.174$, $t = 1.43$, $d = 0.12$), step length ($p = 0.111$, $t = 1.70$, $d = 0.03$) or ground contact time ($p = 0.123$, $t = 0.121$, $d = 0.07$).

TABLE 3 | Running economy values for each participant measured as the distance traveled per liter of oxygen consumed.

Subject	Breast size (cm)	LOW (m/L O_2)	HIGH (m/L O_2)	% Increase
S1	15.0	69.5	80.2	14.5
S2	12.0	68.3	72.6	5.3
S3	9.5	105.7	108.5	1.7
S4	12.0	61.3	64.7	4.6
S5	21.5	65.2	76.7	16.7
S6	13.5	84.9	91.5	6.8
S7	14.5	99.1	110.4	10.4
S8	10.7	88.0	96.4	8.6
S9	12.0	103.9	109.1	4.0
S10	12.0	176.1	189.8	6.8
S11	13.5	74.5	80.7	7.3
S12	14.0	99.0	108.4	8.5
S13	9.0	64.4	65.9	1.3
S14	7.1	101.2	102.9	0.7
S15	8.0	68.2	70.1	1.8
Mean	12.3	88.6	95.2	6.6
SD	3.5	29.1	31.1	4.7

The HIGH compared to LOW support condition was associated with a 6.6% increase in running economy ($p < 0.001$, $t = 6.30$).
*Note: * - denotes a significant difference compared to the LOW condition.*

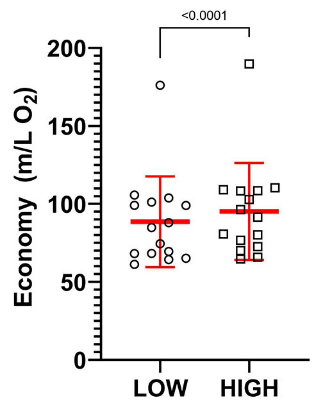

FIGURE 5 | A comparison of individual and mean running economy in the LOW and HIGH support conditions during the treadmill running task. A significant increase in running economy was observed in the HIGH compared to LOW support conditions.

DISCUSSION

The findings of the current study revealed that greater breast support was associated with reduced absolute and relative oxygen consumption and greater running economy during a treadmill running task at a constant mechanical demand. These breast support-related changes in metabolic cost and efficiency occurred in the absence of changes in the temporospatial characteristics of running. Therefore, not only was the mechanical demand of the treadmill running task consistent across both breast support conditions, but the time-space geometry by which the participant elected to accommodate this mechanical demand was similar across both breast support conditions. These findings have substantial implications for recreational and competitive female athletes with regards to sport performance.

Greater breast support was associated with reduced oxygen cost and greater running economy. The current data demonstrated a 6.9% reduction in oxygen consumption when running in the high compared to low support sports bra. Therefore, participants could run faster at a similar oxygen consumption when wearing the high compared to low support sports bra. In the current study, this would equate to running at 3.1 m/s compared to 2.9 m/s, an increase of 0.2 m/s with a consistent oxygen consumption. For all participants, greater breast support was associated with reductions in metabolic cost of running (L O_2) and improvements in running economy (m/L O_2). One candidate mechanism by which greater breast support would improve metabolic cost of running pertains to the biomechanical patterns selected by female runners to avoid breast discomfort. Two related causes of breast discomfort include high breast velocities and forceful breast contact with the anterior trunk wall (McGhee and Steele, 2020b). The high breast velocities are induced by trunk accelerations as the GRF transient propagates through the kinetic chain following initial contact. These trunk accelerations create secondary accelerations of the proximal breast creating high breast velocities as well as high strain magnitudes and high strain rates within the breast tissue (McGhee et al., 2013). In many women, the downward movement of the breasts during the stance phase of running often results in the breasts forcefully striking the anterior trunk wall creating a secondary instance of high breast accelerations (McGhee and Steele, 2020b). These high breast velocities and accelerations are purported to underlie running-related breast discomfort (McGhee and Steele, 2020b). One strategy that could be employed to reduce trunk and breast velocities during running is to reduce stiffness (increase compliance) of the lower limb and increase attenuation of the GRF transient by the ankle, knee and hip joints (Crosslin et al., 2022).

Stiffness is a composite measure that characterizes the magnitude of load applied to a structure and the structure's response to that applied load (Butler et al., 2003; Powell et al., 2014, 2016, 2017). While many variations of stiffness

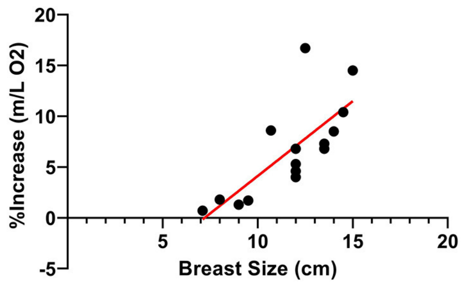

FIGURE 6 | A strong, significant positive relationship was observed between participant breast size (cm) and breast support-induced increases in running economy during the treadmill running task.

TABLE 4 | Average temporospatial characteristics in the LOW and HIGH support conditions.

Subject	Breast size (cm)	Cadence (steps/min)		Step length (m)		Ground contact time (ms)	
		LOW	HIGH	LOW	HIGH	LOW	HIGH
S1	15.0	163	162	0.97	0.97	246	258
S2	12.0	174	181	0.85	0.82	291	291
S3	9.5	181	182	0.95	0.94	305	303
S4	12.0	166	167	0.90	0.89	280	278
S5	21.5	150	155	1.10	1.06	303	299
S6	13.5	170	173	0.90	0.88	250	254
S7	14.5	167	166	1.24	1.25	270	268
S8	10.7	166	166	1.14	1.14	254	249
S9	12.0	175	173	1.12	1.13	235	235
S10	12.0	162	164	1.20	1.18	323	318
S11	13.5	160	158	1.20	1.22	289	284
S12	14.0	157	155	1.29	1.30	318	304
S13	9.0	168	171	1.00	0.98	297	293
S14	7.1	178	177	1.13	1.13	301	302
S15	8.0	166	168	0.75	0.74	291	291
Mean	12.3	166.9	167.9	1.05	1.04	284	282
SD	3.5	8.1	8.5	0.16	0.17	27	24

No differences were observed in temporospatial characteristics.

exist including leg stiffness, vertical stiffness and joint stiffness, previous research has demonstrated that oxygen consumption and running economy are related to lower extremity stiffness values (McMahon and Cheng, 1990; Latash and Zatsiorsky, 1993; Kerdok et al., 2002; Butler et al., 2003; Beck et al., 2016; Moore et al., 2019). It is widely accepted that greater lower extremity stiffness is associated with improved running economy (Kerdok et al., 2002; Butler et al., 2003; Beck et al., 2016; Moore et al., 2019) due to the greater utilization of stored energy in passive, elastic tissues (Latash and Zatsiorsky, 1993). One measure of stiffness that been associated with improved mechanical and metabolic performance during a running task is lower limb and knee joint stiffness (Latash and Zatsiorsky, 1993; Butler et al., 2003; Beck et al., 2016; Powell and Williams, 2018; Moore et al., 2019). Calculated as the ratio of force applied to a structure divided by the deformation of the structure during the load attenuation of the stance phase of running, stiffness characterizes the muscular and skeletal responses of the lower limb to prevent collapse (Butler et al., 2003; Powell et al., 2014, 2016, 2017; Powell and Williams, 2018). Recent research investigating the effect of increasing levels of breast support on knee joint stiffness demonstrated that greater breast support was associated with greater knee joint stiffness values ($p = 0.002$) which were primarily mediated by reductions in the knee joint excursions ($p < 0.001$) rather than increases in knee joint moments ($p = 0.202$) (Crosslin et al., 2022). These stiffness data demonstrate that lower levels of breast support were associated with reduced lower limb stiffness (increased compliance) supporting the postulation that female runners increase lower limb compliance potentially to reduce trunk and breast velocities as well as running-related breast discomfort. These findings also suggest that increased lower limb stiffness associated with greater levels of breast support would be associated improved running performance, both mechanically and metabolically (Latash and Zatsiorsky, 1993; Butler et al., 2003; Beck et al., 2016; Moore et al., 2019).

A second mechanism by which greater levels of breast support may improve running bioenergetics including oxygen cost and running economy pertains to control of the trunk. Trunk motion has been demonstrated to influence the energetic costs of running (Schutte et al., 2015, 2018; De Brabandere et al., 2018). Using trunk-mounted tri-axial accelerometers, Schutte et al. demonstrated that the fusion of several kinematic-based variables could explain variations in energy cost of running (Schutte et al., 2018) while also detecting fatigue-induced changes in running instability (Schutte et al., 2015). Though the equations developed to assess the energy cost of running included temporospatial variables such as step and stride lengths, these algorithms also included non-linear measures of variability including sample entropy (Schutte et al., 2015, 2018). Sample entropy is a measure of signal regularity and evaluates the moment-to-moment fluctuations in a signal as opposed to the signal's central tendency (such as standard deviation or coefficient of variation). The Optimal Movement Variability Theory suggests that biological signals have inherent variability and that a range of optimal variability exists. Further, it suggests that insufficient or excessive variability is indicative of suboptimal performance of the biological system (Stergiou et al., 2006; Stergiou and Decker, 2011). Consistent with previous findings, it could be postulated that in the current study the treadmill running task resulted in greater breast motion (Scurr et al., 2010, 2011b), which altered trunk motion (Risius et al., 2017) and trunk motion variability in the LOW compared to HIGH support sports bra. Though at present, no data exists evaluating the influence of breast support on the non-linear measures of trunk motion variability used by Schutte and colleagues (Schutte et al., 2015, 2018; De Brabandere et al., 2018), emerging data supports the postulation that variability of trunk motion is greater in low- compared to high-support sports bras (Powell et al., 2022). It is possible that increases in trunk rotation variability associated with wearing a low-support sports bra would create greater instability during the running task increasing the energy cost of running. However, it should be noted that no data currently exists supporting this postulation and further investigation is warranted.

While the current findings provide novel insight into the secondary effects of breast support on oxygen consumption and running economy during a treadmill running task, several limitations should be considered. Though our *a priori* power analysis suggested that our sample size was large enough to provide sufficient statistical power, the sample size remains small which may limit generalizability to the greater population. However, the repeated measures design would increase the statistical power of these comparisons by removing a number of confounding variables. Further, our use of Cohen's *d* estimates of effects size (Cohen, 1988) provides a second measure by which the means are compared relative to the pooled variance. The small sample size may have influenced the findings of the correlation analysis and may limit the generalizability of these findings beyond the current study; however, these data clearly indicate that further investigation into the influence of sports bra support on running performance and bioenergetics is warranted. A second limitation pertains to the participant's breast sizes. Specifically, no statistical adjustments were made to account for breast size; however, the correlation analyses highlighted the positive relationship between breast size and breast support-related changes in running performance. Moreover, the strong correlations and large coefficients of determination indicate the meaningful effect of breast support on these measures of oxygen consumption and running economy. Further, our participant cohort was fairly homogenous with smaller breast sizes than those previously studied. A vast majority of research investigating the effects of breast support on running biomechanics and energetics has focused on large breasted women with cup sizes of D or greater. However, the participant cohort in our study had breast sizes between B and DD cup, a potentially more representative sample of competitive and recreational athletes. Though the athletes participating in this study had smaller breast sizes than previous research studies, our data revealed that even smaller breasted females experience improved performance with greater breast support. While, the methods used to quantify breast size in the current study are commonly used in American retail (McGhee and Steele, 2010b) establishments, it has been suggested to poorly measure the size and characteristics of the female breast (Coltman et al., 2017). Though better techniques that would more adequately measure the volume of the breast and better characterize the mechanical characteristics of the breast are in development, the measurement methods used in this study represents one current standard in determining breast size (McGhee and Steele, 2010b). A final limitation of the current investigation was the limited objective data regarding the support provided by each of the sports bras used. Though breast motion can be tracked using a variety of measurement techniques, no systematic study of the support offered by these sports bras has been conducted.

CONCLUSIONS

The findings of the current study demonstrate that greater breast support is associated with improved absolute and relative oxygen consumption as well as running economy. Further, the benefits of increased breast support on oxygen consumption and running economy are influenced by breast size with larger breasted athletes seemingly experiencing greater improvements in running performance than smaller breasted women. These improvements in running performance with increasing breast support show that sports bras should be considered a key component in female athletes' sports equipment and care should be taken to select the proper level of breast support.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Memphis Institutional Review Board (PRO-FY2020-431). The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

Both authors were involved in study conception and design. HF collected data. HF and DP performed data analysis. HF and DP prepared the initial draft of the manuscript. Both authors revised, edited, and approved the final manuscript.

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Comparative analysis of endurance, strength and body composition indicators in professional, under-23 and junior cyclists

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Purpose: To compare endurance, strength and body composition indicators between cyclists of three different competition age categories.

Methods: Fifty-one male road cyclists classified as either junior (n = 13, age 16.4 ± 0.5 years), under-23 [(U23), n = 24, 19.2 ± 1.3 years] or professional (n = 14, 26.1 ± 4.8 years) were studied. Endurance (assessed through a maximal incremental test and an 8-minute time-trial), strength/power (assessed through incremental loading tests for the squat, lunge and hip thrust exercises) and body composition (assessed through dual energy X-ray absorptiometry) were determined on three different testing sessions.

Results: U23 and, particularly professional, cyclists attained significantly (p < 0.05) higher values than juniors for most of the analyzed endurance indicators [time-trial performance, maximum oxygen uptake (VO_{2max}), peak power output (PPO), respiratory compensation point (RCP), and ventilatory threshold (VT)]. Significant differences (p < 0.05) between U23 and professionals were also found for time-trial performance, PPO and VT, but not for other markers such as VO_{2max} or RCP. Professional cyclists also showed significantly (p < 0.05) lower relative fat mass and higher muscle mass levels than U23 and, particularly, juniors. No consistent differences between age categories were found for muscle strength/power indicators.

Conclusion: Endurance (particularly time-trial performance, PPO and VT) and body composition (fat and muscle mass) appear as factors that best differentiate between cyclists of different age categories, whereas no consistent differences are found for muscle strength/power. These findings might help in performance prediction and/or talent identification and may aid in guiding coaches in the design of training programs focused on improving those variables that appear more determinant.

KEYWORDS

predictors, performance, determinants, laboratory, testing, cycling

1 Introduction

The factors that contribute to top-level performance in sports remain largely unknown (Foster et al., 2022). For instance, in road cycling different indicators have been reported as determinants of performance, notably endurance-related indicators such as the capacity to produce high power outputs even in the presence of fatigue (Van Erp et al., 2021, 2021; Mateo-March et al., 2022; Valenzuela et al., 2022) or anthropometric indicators such as a low body mass (van der Zwaard et al., 2019; Leo et al., 2021b). Achieving the top level in any sport and, particularly, in road cycling is a long-term process that takes several years and requires specific characteristics that can be improved along the career trajectory, from junior to under-23 (U23), to finally reaching the professional category. However, there is scarce evidence on the actual physiological/performance differences between cyclists of different age categories that could help identify specific characteristics that should be improved in the younger categories to increase the odds of reaching top-level performance.

As with most endurance sports, cycling performance has been reported to be mainly determined by physiological endurance indicators such as maximum oxygen uptake (VO_{2max}), the so-called ‘lactate threshold’ [or other surrogates such as critical power or ventilatory threshold (VT)], and exercise economy (Joyner and Coyle, 2008; van der Zwaard et al., 2021). Indeed, strong evidence supports these laboratory-based indicators as predictors of cycling performance (Hawley and Noakes, 1992; Nichols et al., 1997; Bishop et al., 1998, 2000; Balmer et al., 2000; Bentley et al., 2001; Amann et al., 2006), and some studies have reported that indicators such as maximal aerobic capacity [represented by VO_{2max} or peak power output (PPO)] might be positively associated with the probability of a junior cyclist reaching the professional category (Svendsen et al., 2018). Controversy exists, however, on whether these endurance indicators can accurately differentiate cyclists of different age categories. Thus, whereas some authors have found a higher VO_{2max} or PPO in professional cyclists than in cyclists of lower categories [amateur (~22 years) or junior (~18 years)] (Pérez-Landaluce et al., 2002), have failed to find such differences (Marín-Pagán et al., 2021).

Notably, while some studies have compared the performance (Leo et al., 2022), training/competition characteristics (Leo et al., 2021a) or endurance capabilities (Pérez-Landaluce et al., 2002; Leo et al., 2021a; Marín-Pagán et al., 2021) between cyclists of different age categories, there is little or no evidence on whether other important factors such as muscle strength or body composition also differ. Accumulating evidence suggests that muscle strength/power plays a major role in cycling performance. For example, Kordi et al. recently reported that knee extension maximum voluntary torque was positively associated with both critical power and with the amount of work that can be completed above this intensity (known as W’ and considered as a marker of the so-called “anaerobic” capacity) (van der Zwaard et al., 2019; Kordi et al., 2021). Likewise, body composition has been reported to condition cycling performance. For instance, muscle mass indicators such as quadriceps volume have been identified as one of the main determinants of peak power production capacity and W’ in cyclists (Miura et al., 2002; Kordi et al., 2018, 2020a; van der Zwaard et al., 2019; Douglas et al., 2021). To the best of our knowledge, however, no previous study has determined whether strength/power or body composition indicators differ between cyclists of different age categories.

The aim of the present study was, therefore, to compare endurance, strength and body composition indicators between cyclists of three different categories (junior, U23 and professional).

2 Materials and methods

2.1 Participants

Fifty-one male road cyclists classified as junior (n = 13, age 16.4 ± 0.5 years), U23 (n = 24, 19.2 ± 1.3 years) or professionals [*Union Cycliste Internationale* (UCI) Pro-Team] (n = 14, 26.1 ± 4.8 years) volunteered to participate in the study. U23 and professional cyclists competed actively at national or international level (including in European or World Championships with the national team of their country of birth). All cyclists were assessed at the end of the ‘pre-season’ period, after at least 2 months had elapsed since the last competition of the previous season. To participate in the study, cyclists had to be free of musculoskeletal injuries or other conditions that could hinder their participation. They were all informed of the study procedures and provided written informed consent. The study was approved by the Ethical Committee of Alcorcón University Hospital (approval number 19/86), and all procedures were conducted following the standards established by the Declaration of Helsinki and its later amendments.

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2.2 Study design

The study followed a cross-sectional observational design. Participants visited the laboratory on three different days interspersed by 48 h. All tests were performed at approximately the same time of the day and under the same conditions (temperature 20 ± 3 °C, humidity 25 ± 3%). Subjects were instructed to maintain their normal dietary pattern and to refrain from doing intense exercise and consuming ergogenic aids/caffeine 48 h before each testing session. The first laboratory visit consisted of body composition assessment and a maximal incremental cycling test. During their second visit, subjects completed strength tests, and during the third visit they performed a simulated 8-minute time-trial.

2.3 Measures

2.3.1 Body composition

Height was determined using a wall stadiometer (Seca 437). Weight and body composition [whole body fat and muscle mass, and bone mineral content (BMC)] was measured by dual energy X-ray absorptiometry (DXA, Hologic QDR series Discovery; Bedford, MA). DXA assessments were performed at least 2 days after the last exercise session. Participants were recommended to maintain a similar eating and sleeping routine the day before each testing session and were advised to be euhydrated.

2.3.2 Incremental cycling test

Cyclists performed a graded exercise test on their own bikes, which were placed on a validated indoor trainer (Hammer, CycleOps, Madison, WI) (Lillo-Bevia and Pallarés, 2018). They started with a standardized 10-minute warm-up at 75 W, and they subsequently accomplished a maximal incremental cycling test with an initial workload of 75 W, increasing by 5 W every 12 s (ramp-like protocol) until volitional exhaustion or when pedaling cadence could not be maintained above 60 rpm. Gas exchange data were collected breath-by-breath (Ultima Series Medgraphics, Cardiorespiratory Diagnostics, Saint Paul, MN). The VT was determined as the workload at which an increase in both the ventilatory equivalent for oxygen ($VE{\cdot}VO^{-1}$) and end-tidal partial pressure of carbon dioxide ($PetCO_2$) occurred with no concomitant increase in the ventilatory equivalent for carbon dioxide ($VE{\cdot}VCO^{-1}$), whereas the respiratory compensation point (RCP, also termed "second ventilatory threshold") corresponded to the work rate at which both $VE{\cdot}VO^{-1}$ and $VE{\cdot}VCO^{-1}$ increased together with a decrease in $PetCO_2$ (Lucía et al., 2000). PPO was defined as the highest power output value reached during the test, and VO_{2max} was defined as the highest VO_2 value (mean of 10 s) attained during the test.

2.3.3 Muscle strength/power

Participants performed an incremental loading test on a Smith machine to assess muscle strength and power-related outcomes in the squat, lunge and hip-thrust exercises, as explained elsewhere (Gil-Cabrera et al., 2021; Valenzuela et al., 2021). Bar mean propulsive power (MPP) during the concentric phase was measured with a validated linear position transducer (T-Force System; Ergotech, Murcia, Spain) (Martínez-Cava et al., 2020). The initial weight was 20 kg (i.e., only the bar), and the load was increased by 10 kg until a decrease in MPP was observed in two consecutive loads. Participants performed three consecutive repetitions with each load, and a 2-minute rest was allowed between loads. We analyzed the highest MPP registered for each exercise and the one-repetition maximum (1RM) was estimated as explained elsewhere (Gil-Cabrera et al., 2021; Valenzuela et al., 2021).

2.3.4 Time-trial

During the third visit, cyclists performed a simulated 8-minute time-trial after a standardized 10-minute warm-up at 60% of their PPO. Participants received no instructions regarding pacing and were blinded to power output values during the trial, but they were instructed to attain the highest mean power output possible, and they were allowed to adjust resistance by changing the gears of the bicycle. The mean power output during an 8-minute time trial has been reported as a valid indicator of performance in cyclists, being also correlated with laboratory-based performance indicators (e.g., lactate threshold) (Klika et al., 2007; Gavin et al., 2012; Sanders et al., 2020).

2.4 Statistical analysis

Data are presented as mean ± SD. Normality (Kolmogorov–Smirnov test) and homoscedasticity (Levene's test) of the data were checked prior to any statistical treatment. Differences between age categories were performed by one-way analysis of variance. In order to reduce the risk of type I error, Bonferroni post-hoc tests were only conducted when a significant group effect was found. Effect sizes (Cohen's d) were computed to examine the magnitude of the differences and considered small, moderate, large, very large and extremely large ($d > 0.1$, > 0.3, > 0.5, > 0.7 or > 0.9, respectively) (Hopkins et al., 2009) (Hopkins et al., 2009). Statistical analyses were performed with specific statistical software (SPSS 26.0, Inc., Chicago, IL, United States), setting the alpha for significance at 0.05.

3 Results

Differences between age categories for endurance, strength and body composition indicators are shown in Table 1, Table 2 and Table 3, respectively.

A significant group effect was observed for all endurance indicators, with a linear increase from juniors to professionals in

TABLE 1 Differences in endurance indicators between groups.

Variable	Professional	U23	Junior	Main *p*-value	ES Prof vs. U23	ES Prof vs. junior	ES U23 vs. junior
8-min TT (W)	396 ± 34	365 ± 29	322 ± 35	<0.001***	0.981*	2.144***	1.337**
8-min TT (W/kg)	6.06 ± 0.30	5.68 ± 0.44	5.30 ± 0.30	<0.001***	1.009*	2.533***	1.009*
PPO (W)	478 ± 37	446 ± 35	403 ± 41	<0.001***	0.888*	1.920***	1.128**
Relative PPO (W/kg)	7.31 ± 0.34	6.94 ± 0.44	6.64 ± 0.34	<0.001***	0.941*	1.970***	0.762
VO_{2max} (L/min)	5.49 ± 0.43	5.22 ± 0.47	4.62 ± 0.56	<0.001***	0.599	1.742***	1.160**
Relative VO_{2max} (ml/kg/min)	82.64 ± 3.54	79.79 ± 4.92	74.54 ± 3.55	<0.001***	0.664	2.284***	1.223**
Relative VO_{2max} (ml/kg MM/min)	95.28 ± 4.67	94.21 ± 5.09	88.24 ± 5.88	0.002**	0.219	1.325**	1.085**
PO at RCP (W)	414 ± 37	392 ± 40	339 ± 35	<0.001***	0.570	2.082***	1.410**
Relative PO at RCP (W/kg)	6.34 ± 0.30	6.10 ± 0.58	5.59 ± 0.49	0.001**	0.519	1.846***	0.949**
VO_2 at RCP (%VO_{2max})	95.22 ± 2.87	95.90 ± 2.49	93.36 ± 2.07	0.018*	0.253	0.743	1.109*
PO at VT (W)	315 ± 34	266 ± 68	245 ± 27	<0.001***	0.911***	2.280***	0.405
Relative PO at VT (W/kg)	4.81 ± 0.37	4.15 ± 0.38	4.05 ± 0.42	<0.001***	1.759***	1.920***	0.249
VO_2 at VT (%VO_{2max})	75.20 ± 4.57	70.55 ± 5.26	73.68 ± 6.05	0.031*	0.943*	0.283	0.552

Abbreviations: ES, effect size (Cohen's d); PO, power output; PPO, peak power output; RCP, respiratory compensatory threshold; VO2max, peak oxygen uptake; MM, muscle mass; VT, ventilatory threshold. Significant differences: *$p < 0.05$;**$p < 0.01$;***$p < 0.001$.

TABLE 2 Differences in strength/power indicators between groups.

Variable	Professional	U23	Junior	Main *p*-value	ES Prof vs. U23	ES Prof vs. junior	ES U23 vs. junior
Squat 1RM (kg)	93.29 ± 20.83	87.17 ± 16.71	81.38 ± 12.89	0.206	0.324	0.687	0.387
Squat relative 1RM [kg/body mass (kg)]	1.41 ± 0.30	1.33 ± 0.24	1.33 ± 0.23	0.643	0.294	0.299	0.000
Squat MMP (W)	604 ± 175	556 ± 118	474 ± 76	0.036*	0.321	0.963*	0.826
Squat relative MMP [W/body mass (kg)]	9.07 ± 2.39	8.47 ± 1.59	7.71 ± 1.34	0.154	0.295	0.701	0.516
Hip thrust 1RM (kg)	113.64 ± 45.87	105.29 ± 29.54	107.85 ± 19.74	0.753	0.216	0.163	0.101
Hip thrust relative 1RM [kg/body mass (kg)]	1.70 ± 0.63	1.60 ± 0.40	1.74 ± 0.26	0.627	0.189	0.083	0.415
Hip thrust MMP (W)	472 ± 162	471 ± 126	504 ± 120	0.760	0.006	0.224	0.268
Hip thrust relative MMP [W/body mass (kg)]	7.07 ± 2.23	7.17 ± 1.73	8.15 ± 1.88	0.259	0.050	0.523	0.542
Split squat 1RM (kg)	51.50 ± 26.15	55.33 ± 18.85	54.31 ± 10.87	0.844	0.168	0.140	0.066
Split squat relative 1RM [kg/body mass (kg)]	0.77 ± 0.37	0.84 ± 0.26	0.88 ± 0.17	0.576	0.218	0.382	0.182
Split squat MMP (W)	285 ± 158	309 ± 106	273 ± 45	0.619	0.178	0.103	0.442
Split squat relative MMP [W/body mass (kg)]	4.25 ± 2.24	4.68 ± 1.44	4.43 ± 0.73	0.709	0.228	0.108	0.218

Abbreviations: 1RM, one-repetition maximum; ES, effect size (Cohen's d); MMP, maximum mean power. Significant differences: *$p < 0.05$;**$p < 0.01$;***$p < 0.001$.

most analyzed variables (Table 1). Accordingly, U23 and, particularly, professionals attained significantly higher values than juniors for most of the analyzed endurance indicators (i.e., 8-minute time-trial performance, VO_{2max}, PPO, RCP, and VT). Differences between U23 and professionals were found only for the 8-minute time-trial, PPO and VT (all of them expressed in both absolute and relative units) and for the relative workload (%VO_{2max}) at which the VT occurred. No differences were found for VO_{2max} or RCP. Of note, no consistent linear association (i.e., no increase from juniors to professionals) was observed for the relative workload (%VO_{2max}) at which the VT and the RCP occurred.

TABLE 3 Differences in body composition indicators between groups.

Variable	Professional	U23	Junior	Main *p*-value	ES Prof vs. U23	ES Prof vs. junior	ES U23 vs. junior
Height (cm)	177.03 ± 4.49	178.45 ± 5.40	176.08 ± 5.41	0.394	0.285	0.191	0.438
Body mass (kg)	66.56 ± 6.08	65.57 ± 5.93	61.87 ± 6.23	0.111	0.164	0.761	0.608
BMI (kg/m^2)	21.20 ± 1.12	20.57 ± 1.27	19.94 ± 1.68	0.064	0.526	0.882	0.423
BMC (kg)	2.38 ± 0.28	2.41 ± 0.33	2.18 ± 0.25	0.080	0.098	0.753	0.785
BMC (%)	3.59 ± 0.31	3.67 ± 0.32	3.53 ± 0.24	0.356	0.253	0.216	0.494
Fat mass (kg)	6.50 ± 1.01	7.66 ± 1.26	7.42 ± 1.91	0.050	1.015	0.602	0.148
Fat mass (%)	9.78 ± 1.33	11.66 ± 1.36	11.90 ± 2.31	0.002**	1.025**	1.124**	0.126
Muscle mass (kg)	57.77 ± 5.50	55.49 ± 4.79	52.28 ± 4.87	0.023*	0.442	1.056*	0.664
Muscle mass (%)	86.77 ± 1.31	84.67 ± 1.30	84.58 ± 2.36	0.001**	1.609**	1.147**	0.047

Abbreviations: BMI, body mass index; BMC, bone mineral content; ES, effect size (Cohen's d). Significant differences: *$p < 0.05$;**$p < 0.01$;***$p < 0.001$.

Contrary to endurance indicators, no significant group effects were found for the analyzed strength indicators with the exception of the squat absolute MMP, which was higher in professionals than in juniors (Table 2). Likewise, no significant group effect was found for anthropometric variables such as body mass, BMI, BMC or absolute fat mass (Table 3). However, a significant group effect was found for relative fat mass—with professionals showing a significantly lower relative fat mass than both juniors and U23—as well as for absolute and relative muscle mass, both of which were higher among professionals than in U23 and, particularly, juniors.

4 Discussion

The main finding of the present study is that U23 and, particularly, professional cyclists differed from junior cyclists for most of the laboratory-based endurance indicators (e.g., VO_{2max}, PPO, RCP, VT and simulated 8-minute time-trial performance). Similarly, there were evident anthropometric differences between professional cyclists and the other two groups, including lower relative fat mass and higher muscle mass levels. Finally, professional cyclists also had higher values for many endurance indicators compared with U23 cyclists, although no differences were found for major markers such as VO_{2max}. Likewise, no consistent differences were found between age categories for strength/power indicators. Although longitudinal studies are warranted to confirm the influence of the abovementioned endurance and anthropometric indicators on performance, these findings might serve for performance prediction and talent identification, as well as to aid coaches in the design of training programs aimed at improving those variables that appear more determinant.

The utility of laboratory-based endurance indicators as determinants of cycling performance has been widely reported. In addition to the 8-minute time-trial performance, which can be considered an indicator of 'actual' performance—and indeed differed between all three age categories in the present study—most of the analyzed endurance indicators showed different results between junior cyclists and the remaining age categories, but only some indicators such as PPO (but not VO_{2max}) differed between professionals and U23 cyclists. PPO, therefore, appears as a more sensitive marker of performance than $VO_{2max.}$ In line with this finding, Marín-Pagán et al. (2021) found that relative PPO was greater in U23 cyclists than in junior cyclists, with no differences in VO_{2max}. Moreover, PPO has been reported to be more strongly correlated with cycling performance than VO_{2max} (Bishop et al., 1998, 2000; Bentley et al., 2001). In this line, Menaspà et al. (2012) reported that while VO_{2max} can discern between junior cyclists of different levels, its accuracy to predict future success (becoming professional) is limited. On the other hand, VT was also different between all three age categories, which is also in accordance with previous studies reporting stronger correlations between cycling performance and threshold-related parameters than for other indicators such as VO_{2max} (Nichols et al., 1997; Bishop et al., 1998, 2000; Bentley et al., 2001; Michalik et al., 2019). Thus, PPO and VT appear as more sensitive markers of performance (and a more sensitive differentiating factor between age categories) than VO_{2max} in well-trained or elite cyclists.

It is noteworthy that no linear association (i.e., no consistent increase from juniors to professionals) was observed for the relative workload (%VO_{2max}) at which VT and RCP occurred. The fraction of VO_{2max} that can be sustained for a given period of time has been traditionally proposed as a marker of endurance performance (Joyner and Coyle, 2008), and it has been reported that trained subjects might have their lactate threshold (overall equivalent to ventilatory thresholds) at a higher %VO_{2max} than untrained peers (Joyner and Coyle, 2008), although this is controversial. In the present study U23 cyclists attained the RCP at a higher %VO_{2max} than juniors, but no differences were found between U23 and professionals. Similarly, professional cyclists attained the VT at a higher %VO_{2max} than U23 cyclists, but no differences were found between professionals and juniors, or between U23 and juniors. In line with these findings, a recent study reported that the fraction of % VO_{2max} at which the lactate threshold occurs was a poor individual predictor of performance (running velocity) and did not differentiate between elite, national and recreational runners (Støa et al., 2020). Therefore, the fraction of VO_{2max} at which thresholds occur should not be used individually as a predictor of endurance performance, unless it is used in combination with other parameters such as maximal aerobic speed or PPO (Støa et al., 2020).

Another major finding of the present study was that, although no differences in body mass were found between age categories, professional cyclists had a lower relative fat mass and higher levels of muscle mass than U23 and juniors. Previous studies have suggested that muscle mass indicators (e.g., quadriceps or thigh muscle cross-sectional area or volume) are positively associated with cycling performance, at least for short-duration efforts (Miura et al., 2002; Kordi et al., 2018, 2020a). In turn, a higher body mass can be negatively associated with performance (i.e., riding speed) owing to the influence of gravity, particularly on the steepest slopes. Thus, it seems that professional cyclists present with higher levels of muscle mass, which can be potentially associated with a greater power production capacity, but in turn a lower fat mass, which enables them to maintain an optimal body mass. Body composition appears, therefore, as a major differentiating factor between cyclists of different age categories.

Contrary to the findings for endurance indicators and body composition, no consistent differences between age categories were found for muscle strength/power indicators. A positive association between maximal strength and cycling performance has been previously reported, at least for short-duration efforts (Kordi et al., 2018, 2021). However, the association between strength capabilities and performance on longer efforts remains unclear. For instance, no associations have been found between critical power and knee extensor torque or back squat 1RM (Kordi et al., 2018; Byrd et al., 2021). Thus, although strength training has proven beneficial for cycling performance (Rønnestad et al., 2015, 2017; Kordi et al., 2020b), strength/power levels measured through an incremental loading test on a Smith machine in three different exercises seem not to be a major determinant of performance.

Some limitations of the present study should be noted. Despite the observed differences between groups, the cross-sectional design of the study precludes from drawing conclusions on performance prediction. Therefore, longitudinal studies are warranted to determine whether these variables could be used to accurately predict performance in young cyclists. Moreover, given that a large number of variables was assessed, the presence of type I error should not be disregarded. However, it must be noted that most variables would remain significant even when applying a stringent threshold p-value (i.e., $p < 0.001$). Finally, some methodological considerations should be also taken in mind. We used an incremental ramp protocol with short steps, which might influence the absolute and relative (%VO_{2max}) position of ventilatory thresholds compared to longer steps (Bentley et al., 2007; Michalik et al., 2019). Moreover, the inclusion of a longer (e.g., 20 or 40 km) time trial, of other strength/power measures such as isometric strength tests (maximal torque and rate of force development) or Wingate anaerobic test, or other body composition indicators such as quadriceps' cross-sectional area, could have provided additional information.

In summary, endurance indicators (e.g., VO_{2max}, PPO, RCP, VT, simulated 8-minute time-trial performance) seem to be the main differentiating factor between junior cyclists and higher categories. Smaller, yet significant, differences in endurance indicators were also found between U23 and professional cyclists, with the latter showing higher time-trial performance, PPO and VT, but without differences in VO_{2max} and RCP. Some differences were also found in anthropometric parameters, with professional cyclists showing a lower relative fat mass and higher muscle mass compared with the remaining age categories. No consistent differences were found between age categories for strength/power indicators. Although longitudinal studies are needed to confirm these findings, the present results might help in performance prediction and/or talent identification and could also aid coaches in the design of training programs focused on improving those variables that appear more determinant.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by The study was approved by the Ethical Committee of Alcorcón University Hospital (approval number 19/86). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

Conception and design of the experiments: LA, AM-P, PV, DB-G, CR, LO, VC, and MM-M. Experimental preparation and data collection: LA, AM-P, CR, DB-G, LO, VC, and AS. Analysis and interpretation: DB-G, PV, and LA. Drafting of the manuscript: AL, AS, PV, DB-G, LA, and MM-M. Revision of the manuscript for important intellectual content: AL, AS, PV, DB-G, and LA. All authors read and approved the final version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effect of facemask use on cognitive function during a maximal running aerobic fitness test

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Background: The aim of the present randomized, crossover study was to determine the physiological and cognitive function responses while wearing a facemask during a maximal running aerobic fitness test.

Methods: Fourteen healthy, nonsmoking physical education students (age = 17.5 years, height = 1.72 m, body mass = 70.4 kg) volunteered to participate in this study. They carried out a 20 m multistage fitness test (MSFT) while wearing or not a cloth facemask on two separate occasions performed in random order. The "Rating of Perceived Exertion" (RPE) and the d2 test for visual attention were administered and assessed before and immediately after the MSFT for both conditions (with or without a facemask).

Results: When wearing the facemask, the participants exhibited lower maximal aerobic speed ($p = 0.039$), VO_{2max} ($p = 0.039$), distance covered during the MSFT ($p = 0.057$), and concentration performance ($p < 0.001$), when compared with the control situation (without facemask). Moreover, they made more errors compared with the control condition ($p = 0.021$). The use of a cloth facemask during maximal endurance running tests (such as the MSFT) reduced VO_{2max}, and measures of cognitive performance as assessed by the test of focused visual attention (the d2 test). This data suggests avoiding using a cloth facemask during maximal aerobic fitness tests, and before any tasks that require a high level of visual attention.

KEYWORDS
COVID-19, facemask, exercice, neuropsychological Tests, coronavirus

1 Introduction

Recently, the worldwide spread of the still ongoing "Coronavirus Disease 2019" (COVID-19) pandemic has profoundly disrupted the normality of daily life, forcing populations to practice social distancing and self-isolation. COVID-19 has directly impacted humans' health and affected their lifestyles, including physical activity, nutrition, and sleep behavior (Ammar et al., 2020; Znazen et al., 2021). The pandemic has had cascading and compound effects involving many domains and sectors of daily life, such as education, travel, and sport, globally, and resulted in canceling and/or postponing of many events, including major international sports events.

Given that the COVID-19 virus is primarily transmitted among people through respiratory droplets and contact routes, wearing a facemask was mandated in order to prevent the transmission and limit the spread of the virus, thus controlling and containing the infectious outbreak (Hopkins et al., 2021; Matuschek et al., 2020). At the same time, it has been reported that a prolonged use of facemasks may lead to physiological and psychological concerns (Li et al., 2005; Rosner, 2020; Epstein et al., 2021). Chronic use of facemasks may result in an increased hypoxia state, due to the decrease in blood oxygen saturation and increase in heart rate and transcutaneous CO_2 (Li et al., 2005; Beder et al., 2008; Rebmann et al., 2013; Rosner, 2020; Scheid et al., 2020; Epstein et al., 2021). Moreover, it could consequently increase stress levels, mental fatigue, and reaction time, impairing responses to perceptual tasks (Modena et al., 2021; Grimm et al., 2022), resulting in headaches, and making communication more difficult and challenging (Rosner, 2020; Tornero-Aguilera and Clemente-Suárez, 2021; Lee et al., 2022).

Information about the effects of facemask on physiological and cognitive functions during exercise is limited (Shaw et al., 2021a; Slimani et al., 2021). It seems that wearing a mask during exercise imposes extra pressure on ventilation (Hopkins et al., 2021), which may lead to small changes in physiological parameters, such as increased dyspnea, end-tidal CO_2, heart rate and respiratory rate (Shaw et al., 2021b; Hopkins et al., 2021). In addition, contradictory results have been reported on its effect on physical performance. A recent randomized controlled trial of healthy adults aged 18–29 years showed that the use of cloth facemasks led to a 14% reduction in exercise time and 29% decrease in VO_{2max}, attributed to perceived discomfort associated with mask-wearing (Driver et al., 2022). The same authors demonstrated that, when compared with the no-mask condition, participants reported feeling increasingly short of breath and claustrophobic at higher exercise intensities while wearing a cloth facemask. In contrast, a systematic review of the literature and meta-analysis showed that wearing a facemask while exercising had no impact on exercise performance (Shaw et al., 2021b). This contradiction may be due to the type of mask worn and the exercise practiced (do Prado et al., 2022; Fikenzer et al., 2020). In addition, considering that cardiovascular fitness is strongly correlated to cognition (Hötting and Röder, 2013) as well as exercise and physical activity in general (Mandolesi et al., 2018), it is important to evaluate the impact of exercising while wearing a facemask on cognitive functioning. Therefore, the aim of the present study was to determine the physiological and cognitive function responses while wearing a facemask during maximal exercise.

2 Materials and methods

2.1 Participants

Fourteen healthy (9 males and 5 females), nonsmoking, physical education students (age = 17.5 years, height = 1.72 m, body mass = 70.4 kg) volunteered to participate in this study after being informed of the nature and of the possible risks associated with the experiment. We included only participants who 1) are active and healthy; 2) practice only physical education; 3) without co-morbidities like diabetes, hypertension, epilepsy, cardiac illness, asthma, and other respiratory illnesses; 4) have been inactive in the last 48 hhours before the physical activity session; and, 5) have accepted to be involved in the present study.

The cloth mask (Half and quarter masks, Tunisia) was a 3-layer comfortable elastic ear loop: extra-soft ear loops eliminate pressure on the ears with layers composed of non-woven fabric. It can be considered a facemask that is typically used by the general population (Matuschek et al., 2020). Due to its availability and usage frequency by the general population, this type of mask was used in this study. The ethical approval for this study was provided by local institutions and was conducted in accordance with the 1964 Declaration of Helsinki.

2.2 Protocols

The study was carried out by implementing a randomized, crossover design during the COVID-19 pandemic, when the government adopted a package of protective and behavioral measures, such as the closing of universities and schools; avoidance of physical contact, handshakes, hugs, and kisses; wearing of facemasks; and, practicing of social/physical distancing. Each participant completed three 20 m multistage fitness tests (MSFT): one for familiarization with MSFT, one with and one without wearing a facemask. The last two MSFTs were conducted in random order. Each test took place at approximately the same time of the day (±1.5 h) and was separated by at least 3 days. During the first test, anthropometric data were collected. Furthermore, participants familiarized themselves with cognitive tests. During all sessions, no drug was administered. All participants gave maximum effort and were encouraged to do so.

Additionally, the d2 test and the "Rating of Perceived Exertion" (RPE) test were administered at the two-time points (15 min before the MSFT and immediately after the test) across the exercise tests (with and without wearing a facemask) in order to assess cognitive function and perceived exertion. After a 10 min warm-up, participants performed the MSFT and responded to the RPE scale immediately afterward. Participants were advised to avoid exercise, and restrain from caffeine, and alcohol consumption 48 h before each laboratory visit. Moreover, throughout the study, participants were instructed to maintain their regular dietary habits and exercise regimens.

2.3 Evaluations

2.3.1 The 20 m multistage fitness test

The MSFT was carried out as outlined in Léger et al. (1988) study. It was previously validated as a predictor of VO_{2max} (intra-class correlation coefficient = 0.90) in adult people (Chung et al., 2022). The participants ran backwards and forwards between two lines 20 m apart, in accordance with the recorded "beep" sound. Only completed shuttles were considered successful runs. The test commenced with an initial speed of 8 km/h, being gradually increased by 0.5 km/h every minute and was stopped if the participant did not reach the line (within 2 m) for two consecutive ends after being warned. Maximal aerobic speed (MAS) was computed as the velocity of the last successfully completed stage, associated with VO_{2max} for the shuttle run test. VO_{2max} was calculated using the Léger et al. (1988) equation.

2.3.2 Attention assessment

The d2 test was used to determine the level of concentrated visual attention of participants (Brickenkamp and Oosterveld, 2012). It consists of 14 rows with 47 characters per line. These characters are the letters d or p, with a total of one to four dashes above and below each letter. Participants were asked to scan each line and cross out only the characters containing the letter d with two dashes during 20 s. After completion of the d2 test, two variables were calculated: concentration performance (CP) and the total number of errors made by the participants (E). CP is calculated as the number of correctly marked d2-symbols minus the number of incorrectly marked symbols (symbols that are not d2-symbols). The total number of E is assessed as the number of errors made by failing to correctly identify a d2-symbol plus the number of errors made by incorrectly marking symbols that are not d2-symbols. We considered both CP and E in the current study.

2.3.3 Rating of perceived exertion

RPE scale was used to estimate the participants' perceived effort. It ranged between 0 "no perceived effort" (i.e., rest) and 10, which corresponded to "maximal perceived effort" (i.e., the most stressful exercise ever performed) (Borg, 1998).

2.4 Statistical analysis

Descriptive statistical analysis was carried out by computing the means and standard deviations for each of the variables under study. The normality of data distribution was verified by applying the Shapiro-Wilk test, which was preferred over other normality tests, given the sample size employed in the present investigation. Differences for performance-related measures between conditions (wearing a mask or not) were assessed by classical Average-Based Change statistics (ABC) (Estrada et al., 2019), more specifically the Student's t-test for dependent (paired) samples. MainThe main effects for cognitive response (CP, and E), and RPE were studied with repeated measure general linear models (GLM) with condition (wearing a mask or not) and time (PRE and POST) as within factors. Moreover, post hoc analyses were carried out, correcting for multiple comparisons.

Depending on the standard deviations, Glass's delta or Hedge's g was calculated as effect size. The former was computed for performance-related measures. For cognition- and perceived exertion-related measures, the magnitude of the difference between values was measured by using Hedge's g. The computed effect size was interpreted as follows: trivial: 0.0–0.2; small: 0.2–0.5; moderate: 0.5–0.8 and large: ≥ 0.8 (Lovakov and Agadullina, 2021). All statistical analyses were conducted utilizing the commercial software "Statistical Package for Social Sciences" (SPSS version 27.0, IBM, Armonk, NY, USA). Results with *p*-values less than or equal to 0.05 were considered statistically significant.

3 Results

Regardless of condition they were allocated, significant alterations were observed for all measures of interest (all, $p < 0.001$) following MSFT.

3.1 Measures of physical performance

During the experimental condition, the participants showed a 7%, 11% and 17% lower MAS (Glass's delta = −0.85; $p = 0.039$), VO_{2max} (Glass's delta = −0.85; $p = 0.039$), and distance covered during the MSFT (Glass's delta = −0.76; $p = 0.057$) when compared to the control condition, respectively (Table 1).

3.2 Concentration performance

During both the experimental and the control conditions, the participants exhibited significantly lower CP following the MSFT, when compared with PRE ($F_{1,26} = 393.558$, $p < 0.001$, $\eta^2 = 0.938$). There was a significant time × group interaction effect ($F_{1,26} = 32.042$, $p < 0.001$, $\eta^2 = 0.552$). Post hoc analysis showed that, during the experimental condition, the participants

TABLE 1 Comparison of physical performance measures while wearing or not a facemask.

	With facemask (N = 14)		Without facemask (N = 14)		Glass's delta	T value (*p* value)
Parameters	**Mean**	**SD**	**Mean**	**SD**		
Shuttle running (repetitions)	6.57	1.83	7.93	1.77	−0.76 (−1.55; 0.04)	−1.993 (0.057)
Maximal aerobic speed (km/h)	10.71	0.93	11.46	0.89	−0.85 (−1.64; -0.02)	−2.178 (0.039)
VO_{2max} (ml/min/kg)	36.89	5.61	41.39	5.32	−0.85 (−1.64; −0.02)	−2.178 (0.039)

TABLE 2 Comparison of cognitive function following the MSFT, conducted while wearing or not a facemask.

		With facemask (N = 14)		Without facemask (N = 14)		Hedges' g (95% CI)	Main effect	Interactions
Parameters	**Time**	**Mean**	**SD**	**Mean**	**SD**		***p* value [η^2]**	***p* value [η^2]**
Concentration performance	PRE	163.29	11.83	164.64	11.88	2.08 (1.15; 2.98)	**<0.001 [0.938]**	**<0.001 [0.552]**
	POST	146.07	9.83	155.07	10.87			
Total number of errors	PRE	43.71	11.83	42.36	11.88	−0.90 (−1.65; −0.13)	**<0.001 [0.909]**	**0.021 [0.188]**
	POST	65.07	11.22	58.07	9.10			
Rating of Perceived Exertion	PRE	1.14	0.95	0.43	0.51	−0.54 (−1.27; 0.20)	**<0.001 [0.987]**	**0.001 [0.432]**
	POST	9.43	0.65	8.21	0.43			

η^2—partial eta-squared; bold values—statistical significance.

experienced significantly greater decreases in CP compared with the control condition (−11% versus −5%, Hedges' g = 2.08, $p < 0.001$) (Table 2).

3.3 Total number of errors

During both the experimental and the control conditions, the participants had significantly higher number of errors following the MSFT, when compared with PRE ($F_{1,26} = 260.523$, $p < 0.001$, $\eta^2 = 0.909$). There was a significant time × condition interaction effect ($F_{1,26} = 6.036$, $p = 0.021$, $\eta^2 = 0.188$). Post hoc analysis showed that, during the experimental condition, the participants made more errors compared with the control condition (49% versus 37%, Hedges's g = −0.90, $p = 0.021$) (Table 2).

3.4 Rating of perceived exertion

During both the experimental and the control conditions, the participants had significantly higher RPE following the MSFT, when compared with PRE ($F_{1,26} = 1931.651$, $p < 0.001$, $\eta^2 = 0.987$). There was a significant time × condition interaction effect ($F_{1,26} = 9.520$, $p = 0.001$, $\eta^2 = 0.432$). Post hoc analysis showed that, during the experimental condition, the participants experienced a lower increase in RPE compared to the control condition, however, the observed difference was not significant (725% versus 1817%, Hedges' g = −0.54, $p = 0.155$) (Table 2).

4 Discussion

The current study investigated the effects of wearing the facemask during maximal-intensity aerobic endurance testing on physical performance and cognitive function parameters. The main findings were that wearing a facemask negatively affected MAS, predicted VO_{2max}, and cognitive function. Briefly, both concentration performance and the number of errors made decreased and increased to a greater extent during the experimental condition after the MSFT than during the control condition, respectively. Although the difference was not statistically significant, an interesting finding was that, during the experimental condition, the participants experienced group experienced a smaller increase in RPE after the MSFT than during the control condition group. This could be primarily due to the overall exercise volume because MAS and the distance covered during the MSFT were 7% and 17% lower during the experimental condition than during the control condition, respectively.

The results showed significantly lower MAS, VO_{2max}, and covered distance during the MSFT, while the participants wore the cloth facemask, thus indicating that wearing a mask reduces overall aerobic performance. We can assume that physical performance decrements were due to acute hypoxia, which can be explained by narrowing the arteriovenous oxygen difference and reduced maximal cardiac output (Peltonen et al., 2001; Lässing et al., 2020) but this claim needs further investigation. More likely, the primary reason for this could be attributed to perceived discomfort associated with mask-wearing. Namely, in a recent study by Driver et al. (2022), the participants reported feeling increasingly short of breath and claustrophobic at higher exercise intensities while wearing a cloth facemask. The ≈11% VO_{2max} drop when wearing a mask compared to a mask-free environment emphasizes the concerns regarding facemask usage during high-intensity physical activity, but, still, these results are more mask-favorable than those by Driver et al. (2022), who observed a 29% decrease in VO_{2max}. For instance, the higher decrease in VO_{2max} in the study by Driver et al. (2022) compared with the present study may be due to the difference between exercise and environmental conditions (laboratory and field conditions). Furthermore, because the 20 m multistage fitness test was designed to determine the maximal aerobic power (Léger et al., 1988), these results further confirm the findings by Scott et al. (2018), who suggested that benefits from high-load exercise might not be augmented from additional hypoxia as for low- and moderate-load exercise.

There is strong evidence that regular physical activity and structured exercise interventions are associated with improvements in cognitive performance at both high and low intensity (Janssen et al., 2014). In the long-term view, these benefits are most likely related to improvements in cardiorespiratory fitness and consequently to cellular, molecular, and structural changes in brain regions involved in motor-cognitive function (Stillman et al., 2016). However, the benefits of short-term high-intensity exercise on cognitive function are inconclusive (Kao et al., 2017; Samuel et al., 2017), long with the mechanisms underlying those changes (Moreau and Chou, 2019). Our results complement previous findings (Alves et al., 2014; Samuel et al., 2017), showing the significant alteration in attention performance following maximal intensity exercise. Alves and colleagues (2014) showed that a single session of high-intensity interval training (HIIT) interval training reduced selective attention assessed using the Victoria Version of the Stroop test. We found that both groups experienced decrements in focused visual attention tasks whether or not the cloth mask was used, with the mask group showing significantly higher alterations than the no-mask group. The differences between the groups may be explained by various physiological factors, such as inhalation of exhaled CO_2 that was mechanically trapped by the mask, which immediately triggers physiological adaptations to compensate for the lower O2 inhalation, similar to the condition during exercise in hypoxic environments (Peltonen et al., 2001; Lässing et al., 2020). In contrast, recent studies (Goh et al., 2019; Kim et al., 2016; Morris et al., 2020) showed that wearing a facemask during moderate, low and mild-intensity exercise had no effect on motor-cognitive performance. However, perceived dyspnea, manifested by 36% higher breathlessness, was observed when compared to the barefaced control group (Morris et al., 2020). In addition, another study investigated the effects of wearing a facemask during warm-up on attention (Slimani et al., 2021). Although positive changes in attention performance such as increased CP and decreased E were observed between wearing or not a cloth mask and no mask. Methodological differences between studies may have contributed to these discrepancies, as different types of facemasks (Modena et al., 2021) were used, eliciting lower or higher hypoxic environmental conditions. Also, different experimental conditions regarding the intensity of exercise, e.g., the maximum intensity of exercise until exhaustion was used in the present study versus moderate intensity of exercise involved in the study by Slimani et al. (2021) and/or prolonged sitting; and finally, different measures of interest were assessed in the studies by Samuel et al. (2017) and by Alves et al. (2014). These differences may account for some of the inconsistencies between studies that should be investigated in future experimental settings.

This study adds to the literature by providing new evidence about the effect of acute aerobic physical fitness tests with and without wearing a facemask on cognitive function. For example, a single bout of maximal aerobic exercise may have a negative effect on visual attention. Also, wearing a facemask during a physical fitness test can amplify this negative effect.

5 Conclusion

The use of a cloth facemask during maximal endurance running tests (such as the MSFT) reduced MAS, predicted VO_{2max}, and distance covered, as well as measures of cognitive performance assessed by the test of focused visual attention d2. These results suggest avoiding cloth mask use in a sports setting, such as in an open skills, scenario (i.e., team sports), particularly in exercise with high intensity, and before any tasks that require a high level of visual attention. Further studies in different sports, evaluating the effects of prolonged, continuous, and high-intensity interval training while wearing a cloth facemask on physical performance and cognitive function are warranted.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the ethical commitee of Postgraduate School of Public

Health, Genoa, Italy. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

Conceptualization, MS; methodology, MS and NLB; software, MS, AP, and NLB; validation, NLB; formal analysis, MS, AP, EA and NLB; investigation, MS; resources, MS and NLB; data curation, MS and NLB; writing—original draft preparation, MS, HZ, AP, EA, and NLB; writing—review and editing, MS, HZ, AP, EA, and NLB; project administration, MS and NLB; funding acquisition, NLB. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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