



# Physiological responses during a 25-km time trial in elite wheelchair racing athletes

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Received: 4 April 2018 / Revised: 27 July 2018 / Accepted: 28 July 2018  
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## Abstract

**Study Design:** Observational study.

**Objectives:** To characterize the cardiorespiratory and metabolic response of elite wheelchair racing (WCR) athletes during a 25 km, field-based time trial.

**Settings:** University laboratory and field racing course in Urbana, Illinois, USA.

**Methods:** Seven elite WCR athletes (4 men/3 women) with spinal cord injury completed an incremental exercise test to exhaustion on a computerized wheelchair roller system to determine peak cardiorespiratory capacity in the laboratory. The athletes then completed a long-distance, field-based time trial (i.e., 25 km) within 5 days. Energy expenditure was measured continuously during the time trial with a portable metabolic unit. Blood samples were collected to determine blood lactate and glucose concentrations. Core temperature was measured using an ingestible sensor thermistor.

**Results:** Five participants completed the long-distance time trial with usable cardiorespiratory data. Median heart rate and oxygen consumption during the time trial was 93.6% and 76.6% of peak values, respectively. Median energy expenditure was 504.6 kcal/h. There was a significant increase in blood lactate concentration from 0.7 to 4.0 mmol/L after the time trial ( $p = 0.03$ ). There were no changes in blood glucose concentrations after the time trial ( $p = 0.27$ ). Lastly, core temperature significantly increased from 37.1 at baseline to 38.7 °C immediately after the time trial ( $p = 0.01$ ).

**Conclusions:** Elite WCR athletes sustained a high exercise intensity that was consistent across the long-distance time trial, and exercise intensity outcomes were generally lower than those documented for elite able-bodied long-distance athletes in other studies. Our findings provide accurate estimates of energy expenditure that can be used to design effective training and racing strategies for elite WCR athletes.

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## Introduction

Adapted sport (AS) is expanding opportunities for physical activity participation and its associated benefits for athletes with spinal cord injury (SCI) [1]. Wheelchair racing (WCR) is one of the most popular AS options and has been part of the Paralympic movement since 1964 [2, 3]. The participation rates of long-distance WCR have increased substantially over the past two decades (i.e., half-marathon, marathon), and are now almost identical to participation rates observed in able-bodied (AB) runners relative to their respective general populations [4]. Consequently, there has been increasing interest in optimizing WCR performance. Current research pertaining to WCR has primarily focused on optimizing sport-chair design and athlete-chair interface (e.g., wheelchair pushing biomechanics) [3, 5–7], while few studies have examined the

WCR athlete, particularly those involved in long-distance racing events [3, 8, 9].

Most notably, there is limited information describing the physiological response of WCR athletes to long-distance exercise in the field setting. Previous field-based examinations of the physiological response of WCR athletes estimated the mean racing oxygen consumption ( $VO_2$ ) to be 34.2 ml/kg/min during a half-marathon distance [10]. However, these values were inferred from heart rate- $VO_2$  (HR- $VO_2$ ) curves, and were not directly measured. Indeed, many field-based examinations lack real-time measurement of physiological response outcomes due to technological limitations and often omit half-marathon or marathon distances [1, 10]. Describing the real-time physiological response, particularly  $VO_2$ , during long-distance exercise is relevant as it characterizes exercise intensity and is beneficial for planning and evaluating the efficacy of training programs [1, 11]. Furthermore, able-body (AB) research has suggested that  $VO_2$ , expressed as a percentage of  $VO_{2peak}$ , is essential when quantifying exercise intensity and determining the physiological demand associated with a particular form of exercise [12].

Unfortunately, previous research examining WCR has not sufficiently characterized racing intensity relative to peak values, and previous characterizations of real-time physiological responses during long-distance trials have typically been done with simulated treadmill trials that do not account for environmental conditions and potentially underestimate racing intensities [9, 13–15]. Fortunately, the development of portable metabolic measurement systems allow real-time examination of physiological responses in the field setting.

Herein, we conducted a real-time characterization of the physiological demands of a long-distance, field-based time trial in elite WCR athletes, using a portable metabolic system. Such an examination is necessary to provide an accurate estimate of the energetic demands associated with long-distance WCR. This work will address current literature gaps involving elite WCR athletes and help to inform effective, evidence-based training and racing strategies for improving racing performance. Furthermore, the characterization of the energetic demands associated with long-distance WCR may be beneficial when formulating sport-specific nutrition programs for these athletes.

## Methods

### Participants

A sample of seven participants with SCI were recruited from a team of elite WCR athletes approximately 4 months

prior to the 2016 Rio Paralympic Games. Criteria for inclusion were: ages 19–40 years; minimal risk for engaging in physical activity (i.e., reported “no” to all questions on the Physical Activity Readiness Questionnaire) [16]; and actively competing in WCR sport. Exclusion criteria were: tobacco use; diagnosed gastrointestinal tract disease; arthritic conditions or neuromuscular problems that limit participation in physical activity; or pregnancy. Participants were informed of the study purpose, experimental protocol, and potential risks prior to providing written consent to participate. All procedures were approved by the Institutional Review Board at the University of Illinois at Urbana-Champaign and Radford University, and were conducted in accordance to standards for the use of human participants in research as outlined in the Declaration of Helsinki.

### Anthropometrics

Participants transferred onto an examination table in the laboratory and the supine height was recorded to the nearest centimeter using a measuring tape. Weight was measured to the nearest 0.1 kg using a portable digital wheelchair scale (Health o Meter® Professional 2400KL, Pelstar LLC, McCook, IL, USA).

### Cardiopulmonary exercise test

An incremental cardiopulmonary exercise test was administered to determine peak cardiorespiratory fitness ( $VO_{2peak}$ ) under laboratory conditions. The test was performed on a wirelessly controlled wheelchair roller system using the athletes’ personal racing chairs. Resistance on the rollers was set using the computerized system. The protocol began at a resistance of 10% and was increased by 5% per minute until volitional exhaustion. The athletes were asked to maintain a minimum target speed of 21–24 km/h, depending on individual racing performance. Respiratory gases were collected using a two-way, non-rebreathable valve (Hans Rudolph Inc., Shawnee, KS, USA) connected to an open circuit spirometry system (TrueOne 2400, Parvo Medics, Sandy, UT, USA). HR was recorded continuously (Polar Electro Oy, Kempele, Finland), and ratings of perceived exertion (RPE) were recorded every minute. The test was terminated when the athlete could no longer maintain the target speed or volitional fatigue occurred.  $VO_{2peak}$  was determined as the highest recorded 20-s  $VO_2$  value when  $\geq 3$  criteria were satisfied: (1) a plateau in oxygen consumption despite an increase in work rate; (2) respiratory exchange ratio  $\geq 1.10$ ; (3)  $HR_{peak}$  within 10 bpm of age-predicted maximum (i.e.,  $220 - \text{age}$ ); or (4) RPE  $\geq 17$ . Ventilatory threshold (VT) was determined using the V-slope method as previously described [17].

## Long-distance time trial

During the time trial, gas exchange was measured breath-by-breath continuously using a portable metabolic system (COSMED K4b2, Rome, Italy). HR was measured continuously using a chest monitor (Polar Electro Oy, Kempele, Finland). Breath-by-breath data were downloaded from the portable unit and averaged across 1-min intervals using the COSMED K4b2 software. Cardiorespiratory data were expressed for the entire time trial and by quartile based on individual performance times. Values were further expressed as a percentage of  $VO_{2peak}$ ,  $HR_{peak}$ , and VT based on values recorded from the CPET. From respiratory measurements ( $VCO_2$  and  $VO_2$ ), total fat, and carbohydrate oxidation rates were calculated using the non-protein respiratory quotient method with  $VCO_2$  and  $VO_2$  in liters per min (L/min), and oxidation rate in grams per minute (g/min) [18].

## Blood lactate and glucose

Blood samples were drawn from an antecubital vein before and after the time trial. A small sample (1 mL) of whole blood was used to determine lactate and glucose concentrations using an automated biochemical analyzer (YSI 2300 Stat Plus, Yellow Springs Instruments Co., Yellow Springs, OH, USA).

## Core temperature

Core temperature was measured by using the HQ Inc. CorTrack II System (HQ Inc., Palmetto, FL, USA). This system consists of an ingestible sensor capsule that wirelessly transmits core temperature ( $^{\circ}C$ ) to a physiological monitoring system. Participants swallowed the capsule 6–12 h before their designated start time. Core temperature was recorded before and after the trial.

## Experimental design

Each athlete completed two testing sessions separated by 4–5 days. At the first session, participants reported to the research laboratory for the completion of informed consent, demographic information, anthropometric measurements, and a cardiopulmonary exercise test (CPET). The athletes were asked to refrain from caffeine, alcohol, and exercise for 12 h prior to the first testing session. At the second session, the athletes completed a 25-km time trial. This distance was selected by the team coach and researchers as the most effective method to complete a full half-marathon at steady state without interfering with the athletes' training cycle (i.e., full marathon). The racecourse was designed by the team coach to mirror a typical competition road course;

it included both uphill and downhill grades and was a large square designed to ensure that athletes were not advantaged or disadvantaged by wind in one direction. The athletes were asked to refrain from caffeine, alcohol, and exercise for 24 h prior to the time trial, and were provided instructions for ingesting the sensor thermistor.

Each athlete reported to the research laboratory 1 h before their scheduled start time. Upon arrival, a blood sample was drawn to determine baseline lactate and glucose concentrations, and core temperature was recorded. Participants were then fitted with a HR monitor, portable metabolic unit, and facemask. Resting metabolic data were collected for 10 min. Participants then transferred into their personal racing chairs and pushed themselves from the laboratory to the start of the racecourse. The athletes started the time trial in pairs, matched based on their expected finish times, but drafting was not allowed. Coaching and research staff were present throughout the racecourse for safety and support. Immediately after the time trial, a second blood sample was drawn in the laboratory for blood lactate and glucose concentrations, and core temperature was recorded.

## Data analysis

Data analysis was performed using IBM SPSS Statistics (Version 24.0, IBM Corp., Armonk, NY, USA). Descriptive statistics were used to summarize demographic characteristics, racing history, and peak cardiorespiratory responses. Based on the small sample, all data were analyzed using non-parametric statistics and median (interquartile range (IQR)) are reported throughout the text, unless otherwise noted. Mean (SD) values were further calculated for comparison with previous research. Cardiorespiratory and metabolic variables at rest and during the time trial were summarized using descriptive statistics. The cardiorespiratory response across trial quartiles were examined using Friedman's analysis of variance. Significant effects were further decomposed using Wilcoxon's signed-rank tests with correction of  $\alpha$  for multiple comparisons (i.e.,  $0.05/5 = p < 0.01$ ). The change in blood lactate, glucose, and core temperature from pre-trial to post-trial was examined using Wilcoxon's signed-rank tests and statistical significance was set a  $p < 0.05$ .

## Results

### Participants

Table 1 presents the demographic and peak exercise characteristics for all participants. Two participants reported having spina bifida, while the remaining participants reported

**Table 1** Athlete characteristics and peak cardiorespiratory response

Participant	Sex	Age (years)	Height (cm)	Body mass (kg)	Lesion level/impairment	C/IC	TPI (years)	WCR experience (years)	HR <sub>peak</sub> (bpm)	VO <sub>2peak</sub> (ml/kg/min)	VT (ml/kg/min)
1	M	32	153.0	48.5	T6–T7	IC	28	24	183	46.0	35.8
2	M	32	189	66.5	T11	IC	11	9	194	46.4	39.0
3	F	29	154	41.9	L1–L2	C	25	20	174	35.0	25.0
4	F	22	150	52.3	L3	C	16	10	196	41.8	34.8
5	F	27	159	48.7	L2	C	27	20	185	53.3	28.8
6*	M	26	146.0	49.6	T11	IC	26	11	172	46.4	36.7
7*	M	30	195	73.8	T11	IC	17	9	177	47.0	37.9
Median (IQR)	–	29.0 (6.0)	154 (39.0)	49.6 (18.0)	–	–	25.0 (11.0)	11.0 (11.0)	183.0 (20.0)	46.4 (5.2)	35.8 (9.1)
Mean (SD)	–	28.3 (3.6)	163.7 (19.8)	54.5 (11.4)	–	–	21.4 (6.7)	14.7 (6.4)	183.0 (9.4)	45.1 (5.6)	34.0 (5.2)

C complete lesion, IC incomplete lesion, L lumbar, HR heart rate, T thoracic, TPI time post-injury, VO<sub>2</sub> oxygen consumption, VT ventilatory threshold, WCR wheelchair racing

\*Participants who did not complete the time trial with usable data

**Table 2** Race performance and mean cardiorespiratory responses recorded during the 25-km time trial

Participant	Completion time (min:s)	Average racing speed (km/h)	HR (bpm)	HR (% peak)	VO <sub>2</sub> (ml/kg/min)	VO <sub>2</sub> (% peak)	VO <sub>2</sub> (% VT)	RER	EE (kcal/h)	%FAT	%CHO
1	45:15	33.2	182.6	99.8	37.1	80.5	103.4	1.01	548.7	9.0	91.2
2	46:52	32.0	163.9	84.5	35.6	76.6	91.1	0.98	719.0	8.4	91.8
3	47:56	31.3	183.0	105.2	30.8	88	123.3	1.0	385.6	19.6	76.8
4	53:56	27.4	183.5	93.6	24.8	59.3	71.3	0.94	382.8	23.5	72.8
5	50:52	29.5	161.9	87.5	34.0	63.9	118.2	0.93	504.6	6.0	91.3
Median (IQR)	47:56 (6:34)	31.3 (4.2)	182.6 (20.4)	93.6 (16.5)	34.0 (8.5)	76.6 (22.7)	103.4 (39.6)	0.98 (0.07)	504.6 (249.6)	9.0 (14.4)	91.2 (16.8)
Mean (SD)	49:03 (3:36)	30.7 (2.3)	175.0 (11.1)	94.1 (8.6)	32.5 (4.9)	73.7 (11.9)	101.5 (21.1)	0.97 (0.04)	508.1 (138.6)	13.3 (7.3)	84.8 (9.2)

%CHO percentage of carbohydrate utilization, %FAT percentage of fat utilization, EE energy expenditure, HR heart rate, RER respiratory exchange ratio, VO<sub>2</sub> oxygen consumption, VT ventilatory threshold

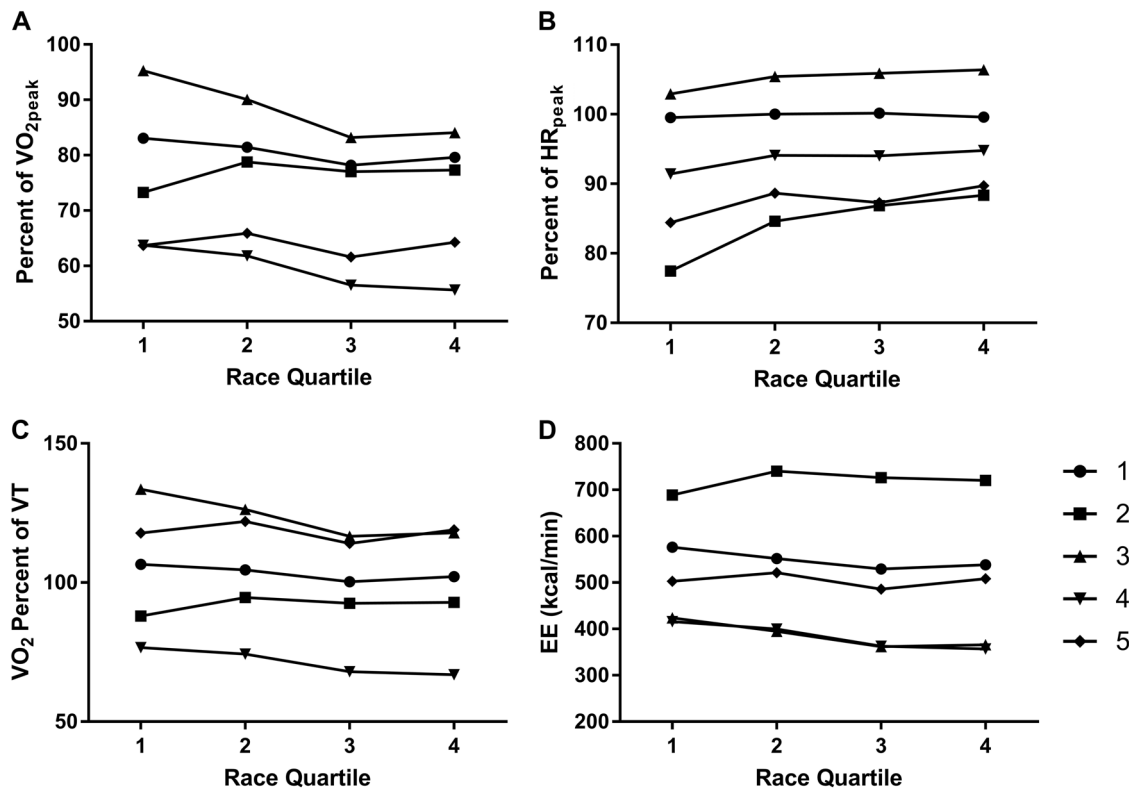
traumatic SCI. Overall, the athletes were aerobically fit relative to persons with SCI (VO<sub>2peak</sub> = 46.4 ml/kg/min) and had extensive competitive racing experience (11 years). All athletes had a racing classification of T53 or T54, indicating normal use of arms and hands, no leg function, and either no/limited trunk function (T53), or limited/normal trunk function (T54) [19].

### Time trial performance

Five participants (2 male, 3 female) completed the 25-km time trial with usable data. Two athletes did not have usable data: one due to an equipment malfunction and one due to acute illness. The average field conditions during the 25-km trials were 22.4 °C, 39.2% humidity, and wind at 20.4 km/h. At rest, HR and VO<sub>2</sub> were 76.9 (9.1) bpm and 4.9 (1.3) ml/

kg/min, respectively. Resting RER was 0.8 (0.1) and energy expenditure was 67.5 (25.1) kcal/h.

Trial performance variables and physiological response variables recorded during the trial are presented in Table 2. The median time to completion was 47:56 (6:34) min at a speed of 31.3 (4.2) km/h. Racing HR and VO<sub>2</sub> were 93.6 (16.5)% and 76.6 (22.7)% of peak values, respectively. Racing VO<sub>2</sub> expressed as a percent of VT was 103.4 (39.6)%. During the trial, RER was 0.98 (0.07) and energy expenditure was 504.6 (249.6) kcal/h. Fat and carbohydrate utilization during the trial were 9.0 (14.4)% and 91.2 (16.8)%, respectively. The cardiorespiratory responses by trial quartile are presented in Fig. 1. Across quartiles, VO<sub>2</sub> ranged from 71.3 to 75.8% of VO<sub>2peak</sub> ( $X^2 = 7.1$ ,  $p = 0.07$ ), HR ranged from 91.1 to 95.8% of HR<sub>peak</sub> ( $X^2 = 10.7$ ,  $p = 0.01$ ), VO<sub>2</sub> as a percentage of VT ranged from 98.2 to



**Fig. 1** Physiological responses recorded during the 25-km time trial by quartile for: **A** percent of peak oxygen uptake ( $VO_{2peak}$ ); **B** percent of peak heart rate ( $HR_{peak}$ ); **C** percent of ventilatory threshold (VT); and **D** energy expenditure (EE)

104.5% ( $X^2 = 7.1$ ,  $p = 0.07$ ), and energy expenditure ranged from 493.2 to 521.5 kcal/h ( $X^2 = 6.4$ ;  $p = 0.10$ ). There were no significant differences between quartiles for any of the cardiorespiratory outcomes using the adjusted  $\alpha$ -level.

There was a significant increase in median blood lactate concentration from 0.7 (0.3) to 3.7 (3.0) mmol/L ( $Z = -2.0$ ;  $p = 0.04$ ) following the time trial. Median blood glucose concentrations did not significantly differ from 80.5 (5.4) to 87.3 (42.3) mg/dL ( $Z = -0.94$ ;  $p = 0.35$ ) following the time trial. Lastly, there was a significant increase in core temperature from 37.3 (0.2) to 38.6 (1.8) °C ( $Z = -2.0$ ;  $p = 0.04$ ) after the time trial.

## Discussion

We conducted the first field-based evaluation of physiological responses of elite WCR athletes during a long-distance time trial. This study was conducted to address current literature gaps pertaining to elite WCR athletes in order to inform the development of effective, evidence-based training/nutrition programs, and racing strategies to improve performance. Importantly, these evidence-based training/nutrition programs will be fundamental for increasing the

efficiency of athletic competition preparation and maximizing athletic performance.

The mean racing  $VO_2$  recorded during the trial was consistent with estimated racing  $VO_2$  (32.7 ml/kg/min) reported from a study involving eight endurance-trained wheelchair athletes (7 men, 1 woman) over 30 years ago [20]. Participants in the current trial sustained a mean racing intensity of 73.7%  $VO_{2peak}$ , similar to that was reported during a 10-km time trial (78%  $VO_{2peak}$ ) on a wheelchair treadmill in 18 elite male WCR athletes [9]. The racing  $VO_2$  of the athletes in the current study was substantially lower than that reported in elite AB runners during sustained long-distance exercise (~80–85%  $VO_{2peak}$ ) [21, 22]. The inability of WCR athletes to reach AB exercise intensities is likely due to the smaller upper extremity musculature used for propulsion compared to the musculature used during running [23]. Based on the response observed during this time trial, coaches and athletes should implement a training intensity of ~75%  $VO_{2peak}$  (or ~90%  $HR_{peak}$ ) when training elite WCR athletes for long-distance competition.

There is extensive evidence on the energetic demands of different types of physical activities in AB populations [12]. However, little evidence exists on the energetic demands of AS events, particularly at the elite level. On average, the athletes in the current study expended 508.1 kcal/h

(138.6 kcal/min) with a substrate utilization composition of 13.3% fat and 84.8% carbohydrate, this is consistent with previous studies involving long-distance WCR athletes at similar intensities [13, 14]. One previous study involving athletes with SCI reported an average energy expenditure of 445.5 kcal/h (7.4 kcal/min) at a blood lactate concentration of 4 mmol/L during an incremental exercise test [13]. Additionally, a separate study examining long-distance WCR athletes reported an energy expenditure of 528.6 kcal/h at a blood lactate concentration of 3.08 mmol/L during prolonged exercise [14]. The small difference between trials is likely explained by the real-time elements of the current study (e.g., humidity and wind resistance) compared to the laboratory setting [13, 14]. Energy expenditure during exercise in WCR athletes is much lower than that reported in AB marathon runners (840–900 kcal/min) [12, 21, 22]. This discrepancy can likely be accounted for by the difference in active muscle mass between WCR and AB running. Similar to elite AB runners, participants relied predominantly on carbohydrate utilization [24]. Coaches and athletes can use these values to determine weekly caloric needs, select appropriate supplements, and construct nutritional plans to satisfy this energetic demand and optimize athletic performance.

Blood lactate concentrations reached 3.4 mmol/L by the end of the time trial. This value is not surprising considering that participants raced at 76% of  $VO_{2peak}$  and 97.3% of VT during the trial. The lactate concentrations from the current study are consistent with previous studies that reported a blood lactate concentration of 3.5–4 mmol/L after long-distance exercise [9, 15]. Blood lactate values in the current study are lower than those reported in a sample of endurance-trained AB athletes after long-distance exercise (8.9 mmol/L) [25]. The lower blood lactate response in the current study is likely multifaceted (e.g., differences in exercise modes, active muscle mass, muscle fiber recruitment patterns), but may partly be explained by the elite level of training of the athletes [26]. Indeed, it has been reported that highly trained athletes have improved lactate clearance rates compared to the general population after exercise [25]. Furthermore, previous studies have speculated that WCR athletes may be able to achieve a balance between lactate production and clearance as deduced from differences in blood lactate concentrations [27]. In response to the long-distance time trial, there were no changes in blood glucose concentrations from pre-trial to post-trial. This finding suggests that liver and muscle glycogen stores were sufficient to meet the increased carbohydrate demand that is experienced by exercising muscles during this long-distance exercise [24].

Core temperature increased significantly by 1.2 °C during the time trial. This is consistent with another study that examined core temperature of trained WCR athletes during

long-distance exercise [28]. It is well documented that individuals with SCI have impaired thermoregulatory capacity compared to their AB counterparts [29]. Impaired autonomic and somatic nervous system function following SCI negatively impacts the ability to regulate skin blood flow and sweating responses [8]. Lower skin blood flow is likely due to the inability to maintain cardiac output during prolonged exercise, and this might impact racing performance and injury risk [30]. Future training programs should include effective cooling strategies to minimize the impact of altered thermoregulation and to improve WCR performance [31].

### Limitations and future directions

There are important limitations of this study that must be considered. First, the sample size was small and limited to elite-level WCR athletes with extensive training experience. Additional data analyses by sex or injury type were not possible due to the sample size, and this will be important to examine in future work. The athletes recruited to this study were all from one training facility, and these results are not applicable to recreational athletes or non-endurance competitors. Another limitation is the lack of American Spinal Injury Association (ASIA) impairment scale scoring of the participants' injuries. Due to the athletes' strict training and racing schedule, intensive pre-time trial procedures (e.g., maximal exercise test) took precedence over confirming ASIA score. We further did not have access to prior medical records of the participants. Another important consideration is the time trial distance (25 km). This distance was chosen by the team coach and researchers as the most effective to complete a full half-marathon at steady state without interfering with the athletes' training cycle. However, the physiological response during a full marathon distance should also be characterized in future studies. Additionally, the examination of the physiological response of athletes with higher SCI would be beneficial as those individuals tend to have greater physiological impairment (e.g., thermoregulatory issues, autonomic dysreflexia) that may affect athletic performance. Another important consideration is that the racecourse was a simulated event, not an actual competition. Although the course was designed to mimic a typical half-marathon race, some factors of a competition may not have been captured. Additionally, the metabolic measurement system used to assess peak fitness was different from the equipment used during the time trial, potentially causing an inconsistency between values recorded from the different devices. Lastly, blood lactate, glucose concentrations, and core temperature were only recorded pre–post. Future studies should examine these variables at multiple time points.

In the current study, we characterized the physiological response of elite WCR athletes to a prolonged bout of

aerobic exercise. Compared to AB long-distance athletes, there is limited evidence on the performance of elite WCR athletes, particularly obtained in settings that closely resemble competitive events. Physiological responses to long-distance aerobic exercise in AB athletes may not be the same as in WCR athletes, and it is imperative that these responses are also characterized. We describe the physiological response during elite WCR, and provide information for athletes and coaches to optimize training programs and racing performance. This characterization of the real-time physiological responses of WCR athletes can be used to inform future research examining the safety and efficiency of exercise training to determine optimal training strategies for WCR athletes.

### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

### References

- Bernardi M, Guerra E, Di Giacinto B, Di Cesare A, Castellano V, Bhambhani Y. Field evaluation of paralympic athletes in selected sports: implications for training. *Med Sci Sports Exerc.* 2010;42:1200–8.
- Cooper RA. Wheelchair racing sports science: a review. *J Rehabil Res Dev.* 1990;27:295–312.
- Cooper RA, Boninger ML, Cooper R, Robertson RN, Baldini FD. Wheelchair racing efficiency. *Disabil Rehabil.* 2003;25:207–12.
- Lepers R, Stapley PJ, Knechtle B. Analysis of marathon performances of disabled athletes. *Mov Sport Sci.* 2014;84:43–9.
- Goosey VL, Campbell IG, Fowler NE. Effect of push frequency on the economy of wheelchair racers. *Med Sci Sports Exerc.* 2000;32:174–81.
- van der Woude LH, Veeger HE, Dallmeijer AJ, Janssen TW, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion. *Med Eng Phys.* 2001;23:713–33.
- Goosey VL, Campbell IG. Symmetry of the elbow kinematics during racing wheelchair propulsion. *Ergonomics.* 1998;41:1810–20.
- Bhambhani Y. Physiology of wheelchair racing in athletes with spinal cord injury. *Sports Med.* 2002;32:23–51.
- Campbell IG, Williams C, Lakomy HK. Physiological and metabolic responses of wheelchair athletes in different racing classes to prolonged exercise. *J Sports Sci.* 2004;22:449–56.
- Asayama K, Nakamura Y, Ogata H, Morita H, Kodama S, Hatada K. Energy expenditure of paraplegic marathon runners measured during a wheelchair marathon. *J UOEH.* 1984;6:121–30.
- Cooper RA, Baldini FD, Boninger ML, Cooper R. Physiological responses to two wheelchair-racing exercise protocols. *Neurorehabil Neural Rep.* 2001;15:191–95.
- Loftin M, Sothorn M, Koss C, Tuuri G, Vanvrancken C, Kontos A, et al. Energy expenditure and influence of physiologic factors during marathon running. *J Strength Cond Res.* 2007;21:1188–91.
- Abel T, Kröner M, Rojas Vega S, Peters C, Klose C, Platen P. Energy expenditure in wheelchair racing and handbiking—a basis for prevention of cardiovascular diseases in those with disabilities. *Eur J Cardiovasc Prev Rehabil.* 2003;10:371–76.
- Knechtle B, Müller G, Willmann F, Eser P, Knecht H. Fat oxidation at different intensities in wheelchair racing. *Spinal Cord.* 2004;42:24–28.
- Lakomy HK, Campbell I, Williams C. Treadmill performance and selected physiological characteristics of wheelchair athletes. *Br J Sports Med.* 1987;21:130–33.
- Bredin SSD, Gledhill N, Jamnik VK, Warburton DER. PAR-Q+ and ePARmed-X+ new risk stratification and physical activity clearance strategy for physicians and patients alike. *Can Fam Physician.* 2013;59:273–7.
- Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol.* (1985). 1986;60:2020–7.
- Frayn KN. Calculation of substrate oxidation rates in vivo from gaseous exchange. *J Appl Physiol Respir Environ Exerc Physiol.* 1983;55:628–34.
- Winnick JP. *Adapted physical education and sport.* 5th ed. Champaign, IL: Human Kinetics; 2010.
- Asayama K, Nakamura Y, Ogata H, Hatada K, Okuma H, Deguchi Y. Physical fitness of paraplegics in full wheelchair marathon racing. *Paraplegia.* 1985;23:277–87.
- Costill DL, Fox EL. Energetics of marathon running. *Med Sci Sports.* 1969;1:81–6.
- Williams C, Nute ML. Some physiological demands of a half-marathon race on recreational runners. *Br J Sports Med.* 1983;17:152–61.
- Carter H, Jones AM, Barstow TJ, Burnley M, Williams CA, Doust JH. Oxygen uptake kinetics in treadmill running and cycle ergometry: a comparison. *J Appl Physiol.* 2000;89:899–907.
- Hawley JA, Leckey JJ. Carbohydrate dependence during prolonged, intense endurance exercise. *Sports Med.* 2015;45:5–12.
- Jenkins DG, Quigley BM. Blood lactate in trained cyclists during cycle ergometry at critical power. *Eur J Appl Physiol.* 1990;61:278–83.
- Bergman BC, Wolfel EE, Butterfield GE, Lopaschuk GD, Casazza GA, Horning MA, et al. Active muscle and whole body lactate kinetics after endurance training in men. *J Appl Physiol.* (1985). 1999;87:1684–96.
- Hooker SP, Wells CL. Physiologic responses of elite paraplegic road racers to prolonged exercise. *J Am Paraplegia Soc.* 1990;13:72–7.
- Price MJ, Campbell IG. Thermoregulatory and physiological responses of wheelchair athletes to prolonged arm crank and wheelchair exercise. *Int J Sports Med.* 1999;20:457–63.
- Hopman M, Oeseburg B, Binkhorst R. Cardiovascular responses in persons with paraplegia to prolonged arm exercise and thermal stress. *Med Sci Sports Exerc.* 1993;25:577–83.
- Wilson TE, Crandall CG. Effect of thermal stress on cardiac function. *Exerc Sport Sci Rev.* 2011;39:12–17.
- Goosey-Tolfrey V, Swainson M, Boyd C, Atkinson G, Tolfrey K. The effectiveness of hand cooling at reducing exercise-induced hyperthermia and improving distance-race performance in wheelchair and able-bodied athletes. *J Appl Physiol.* 2008;105:37–43.