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Relationship between second lactate threshold and onset of blood lactate accumulation during graded incremental wheelchair propulsion exercise in elite wheelchair endurance athletes.

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Running Title:
Comparison of LT2 and OBLA in elite wheelchair racers

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Abstract:

This study aimed to assess individual lactate thresholds during wheelchair propulsion exercise in elite wheelchair racers, investigate inter-individual variations in blood lactate concentration at their thresholds, and examine the practicality of using fixed blood lactate concentration as a threshold determination method. Three elite male wheelchair racers performed a graded incremental wheelchair propulsion exercise test on a wheelchair ergometer. The test consisted of five 3-min stages at velocities ranging from 18 to 28 km/h, followed by a continuous incremental exercise to exhaustion. Blood lactate concentration, ventilatory parameters, pulse rate, and rating of perceived exertion were measured throughout the test. Individual second lactate thresholds (LT2) were determined primarily based on an acceleration in blood lactate concentration increase, with supporting evidence from other physiological parameters. The onset of blood lactate accumulation (OBLA, fixed 4 mmol/l threshold) was also determined for comparison. All participants exhibited notably high blood lactate concentrations at LT2 (5.8-7.7 mmol/l), substantially exceeding the conventional 4 mmol/l reference. The physiological parameters at LT2, including the percentage of peak oxygen uptake (79.2-86.7%) and the percentage of peak pulse rate (86.5-93.1%), were consistent with previously reported values. OBLA occurred at significantly lower exercise intensities than LT2, with associated physiological parameters falling below literature values. Despite the small sample size, LT2 intensity showed a positive correlation with race performance ($r = 0.92$), while OBLA intensity showed a negative correlation ($r = -0.77$). This study demonstrates that appropriate evaluation of individual LT2 during wheelchair propulsion is feasible in elite wheelchair racers. The fixed 4 mmol/l threshold may be inappropriate for elite wheelchair racers. Our findings emphasize the importance of individual threshold assessment for effective training prescription.

Keywords:
Wheelchair propulsion, Wheelchair Racing, Lactate Threshold, LT2, OBLA.

Main Text:

Introduction

In endurance sports, athletes' maximal lactate steady state (MLSS) serves as a crucial determinant of their performance. The MLSS represents the highest exercise intensity at which lactate production and elimination are kept in equilibrium (for review, see Billat et al[1]). At or below this intensity, athletes can maintain prolonged exercise depending primarily on oxidative energy metabolism. Conversely, above this intensity, anaerobic glycolysis is enhanced substantially, lactate production increases, and lactate concentration in blood, and presumably in muscle, begins to accumulate. Consequently, athletes become unable to maintain prolonged exercise. The precise assessment of MLSS plays an important role in predicting athletes' race performance and optimizing their training. By using MLSS as a reference for training prescription, coaches and athletes can effectively manage physiological intensity during training. Therefore, regular MLSS assessment provides significant benefits in athletic monitoring.

While the benefit of MLSS assessment is undoubted, it can be time-consuming and physically demanding for athletes: the gold standard method of assessing MLSS requires multiple constant-load exercise trials of at least 30 min on different days at different exercise intensities.[2-3] Researchers have therefore developed more practical methods as alternatives, particularly by examining physiological responses during graded incremental exercise tests. During these tests, several physiological parameters, such as blood lactate concentration and ventilation, show some characteristic changes as exercise intensity gradually increases. These changes reflect transitions in athletes' energy metabolism. Typically, blood lactate concentration (BLa) and minute ventilation ($\dot{V}E$) show two inflection points during incremental exercise. The MLSS corresponds to the second inflection point. This point is referred to as the individual anaerobic threshold (IAT),[4] the second lactate threshold (LT2, this term is used in this study),[5] the lactate turn point (LTP),[6-7] the second ventilatory threshold (VT2),[5,8] or the respiratory compensation point (RCP).[9] Various methods have been proposed for determining LT2 from individual BLa plots during incremental tests, including visual inspection approaches,[7] lactate increment-based approaches,[10] and geometric analyses of the regression curve.[11] As these methods are sometimes criticized for their potential subjectivity, more objective methods have also been proposed, such as the fixed BLa method. A BLa of 4 mmol/l is the most widely used reference point, known as the onset of blood lactate accumulation (OBLA).[12-13] While OBLA has shown practical correlation with endurance performance,[12] it may not accurately reflect individual MLSS due to inter-individual variations in BLa at MLSS (possibly ranging from 3-10 mmol/l).[13-14]

While LT2 and OBLA determination through graded incremental exercise testing has been extensively studied in various sports, research for wheelchair propulsion remains limited. Some researchers have investigated the thresholds of wheelchair athletes using arm-cranking exercises.[15] However, because BLa at the thresholds may depend on the motor pattern of the exercise,[16] applying their results to wheelchair propulsion exercise is questionable.[17] Other studies used graded incremental wheelchair propulsion exercise on a treadmill and examined LT2[18] or OBLA.[19-20] However, the majority of those studies only employed team sports wheelchair athletes. In the few studies that have subjected endurance wheelchair athletes to wheelchair propulsion exercise, only low thresholds such as the first ventilatory threshold (VT1) have been examined,[21-22] or MLSS alternatives have been estimated using methods other than graded incremental exercise testing (i.e., the lactate minimum, which was reported to differ substantially in BLa from MLSS[23]). To our knowledge, no study has assessed LT2 or OBLA in endurance wheelchair athletes using graded incremental wheelchair propulsion exercise. Additionally, few discussions have been made on the practicality of using the fixed threshold of 4 mmol/l for threshold determination in this exercise. Therefore, this study aimed to assess the LT2 of endurance wheelchair racers using wheelchair propulsion exercise, to investigate the inter-individual variation in BLa at LT2, and to examine the potential use of a fixed BLa method as an alternative to LT2 or MLSS assessment in this exercise.

Methods and Materials

Participants

Three elite male wheelchair long-distance racers participated in this study (race class category, T54; age, 38 ± 7 years; body mass, 65.3 ± 2.3 kg; wheelchair mass, 9.2 ± 0.5 kg; mean ± standard deviation). All the participants had careers of more than 10 years as para-athletics athletes and had experience as national representatives. The study protocol was approved by the research ethics committee of Japan Institute of Sports Sciences (reference number 2022-019). All participants were informed about the purpose and procedure of this study and provided written informed consent prior to participation.

Exercise Equipment

A wheelchair roller ergometer (Esseda, Lode BV, Groningen, Netherlands) was used for the graded incremental wheelchair propulsion exercise test. Participants used their own racing wheelchairs. Dynamic calibration of the ergometer was performed prior to each test to account for individual differences in wheelchair-participant combination friction.[24]

A constant rolling resistance coefficient of 0.016 was set for all participants throughout the test. This coefficient was determined to approximate the friction that wheelchair and athlete would experience during a road race. Race friction comprises rolling resistance and drag resistance.[25] Rolling resistance can be calculated using the rolling resistance coefficient. Although no literature has reported this coefficient for racing wheelchair on roads, a value of

0.003 was determined with reference to racing bicycles.[26-27] Drag resistance was calculated using the effective frontal area of the wheelchair-athlete combination, air velocity opposing wheelchair progression, and air density. Based on literature examining the effective frontal area of wheelchair racers,[28] an area value of 0.26 m^2 was assumed. Using this value with an opposing air velocity of 28 km/h (equals to the velocity at the last stage of the incremental test) and air density of 1.225 kg/m^3 (international standard atmosphere), the assumed drag resistance was calculated. This drag resistance was converted into an equivalent rolling resistance coefficient of 0.013 using the participants' averaged wheelchair-athlete combination mass. The final rolling resistance coefficient (0.016) was determined as the sum of these resistance values.

Measurement Protocol

Participants warmed up with self-selected resistance coefficients and velocities for over 5 min on the ergometer, followed by short sprints for familiarization. After substantial passive rest, the graded incremental test began. The first part of the test consisted of five 3-min exercise stages with 1-min between-stage rests. Participants controlled their velocity to match target values for each stage (18, 21, 24, 26, and 28 km/h for the first to fifth stages, respectively) by monitoring a velocity meter displayed on a screen. As the ergometer's left and right rollers were controlled independently, the average velocity was displayed. The left and right velocities were also monitored to ensure minimal differences. Participants reached the target velocity in the first 20-30 s of each stage. The actual velocities during the last 2.5 min and the last 1 min of each stage were collected. The difference between these velocities was found to be minimal (0.03 km/h on average), therefore the actual velocity during the last 1 min was used for analysis.

After the fifth stage, participants took a 5-min rest before beginning the second part of the test: a continuous incremental exercise to exhaustion. Initial velocity was set at 26 km/h and increased by 1 km/h every minute. The test was terminated when participants could no longer maintain the target velocity despite strong verbal encouragement. The velocity was checked every 15 s, and if the target velocity was not achieved even momentarily within this 15-s period, it was deemed that the velocity was not maintained.

Data Collection

Capillary blood samples were obtained from the earlobe for BLa measurement after each stage in the first part and at 1, 3, and 5-min after the termination of the second part for peak BLa (BLa_{peak}) determination. Samples were analyzed immediately using a handheld lactate analyzer (Lactate Pro 2 LT-1730, Arkray, Japan). Spirometric data were recorded continuously using an expiratory gas analyzer (Aeromonitor AE310-S, EXP mode, Minato Medical Science, Japan). Oxygen uptake ($\dot{V}O_2$) and $\dot{V}E$ during the last 1 min of each stage were calculated for analysis. Stage $\dot{V}O_2$ values were also represented as percentages of peak $\dot{V}O_2$ (%$\dot{V}O_{2peak}$), which were extracted from second-part data averaged at 30-s intervals. Pulse rate (PR) was recorded continuously using a pulse rate monitor attached on the upper arm or forearm of participants (Verity sense, Polar, Finland). PR values were collected at each stage end and at peak during the second part (PR_{peak}). Stage PR values were expressed as percentage of PR_{peak} (%PR_{peak}). Rating of perceived exertion (RPE) was recorded using Borg's 6-20 scale[29] immediately after each stage.

Lactate Thresholds Determination

Individual LT2 determination was primarily based on BLa changes, supported by changes in other physiological parameters. BLa was plotted against actual velocity from each stage, and rate changes between stages were also calculated. LT1 was not determined in this study as it was not of interest. LT2 was determined as the stage before a second substantial acceleration in BLa increase. The ventilatory threshold (VT2) was determined similarly to support LT2 determination. %$\dot{V}O_{2peak}$, %PR_{peak}, and RPE at each stage were also referenced to support LT2 determination, based on their proximity to those values at MLSS, LT2, or RCP in wheelchair athletes reported in the literature (76-78%, 92%, and 15-16 for %$\dot{V}O_{2peak}$, %PR_{peak}, and RPE, respectively)[18,23]. After the LT2 determination, $\dot{V}O_2$, %$\dot{V}O_{2peak}$, PR, %PR_{peak}, and RPE at the LT2 stage were collected as the relevant physiological parameter values.

For OBLA determination, stages with the BLa of just below and above 4 mmol/l were identified. Assuming linear changes between these stages, $\dot{V}O_2$, $\%\dot{V}O_{2peak}$, PR, $\%PR_{peak}$, and RPE corresponding to 4 mmol/l were calculated.

Correlation to Race Performance

LT2 and OBLA were examined for relationship to race performance. All participants competed in the same wheelchair marathon race approximately one month before the incremental test. Average race velocity was calculated as a performance parameter. Correlations between race performance and exercise intensities at LT2 and OBLA were examined. Due to the small sample size (N = 3), no significance testing was performed.

Results

Three participants demonstrated different BLa responses during the incremental test (Figure 1). Participant A showed an exponential increase, participant B exhibited a linear increase followed by a sharp elevation in the final stage, while participant C demonstrated a continuous linear increase without distinct inflection points.

[Figure 1. Changes in blood lactate concentration during graded incremental wheelchair propulsion exercise.]

Regarding spirometry, participant B's data could not be collected during the first part of the test due to equipment problems. For $\dot{V}E$, participant A showed a slightly accelerated increase at the fourth stage and a marked increase at the fifth stage, while participant C showed linear increases throughout without inflection points (Figure 2). $\dot{V}O_2$ exhibited constant linear increases in both participants A and C (Figure 3).

[Figure 2. Changes in minute ventilation during graded incremental wheelchair propulsion exercise.]

[Figure 3. Oxygen uptake during graded incremental wheelchair propulsion exercise.]

PR exhibited gradual increases in all participants (Figure 4). RPE also increased gradually in all participants (Figure 5), although participant C consistently reported lower values compared to others.

[Figure 4. Pulse rate response during graded incremental wheelchair propulsion exercise.]

[Figure 5. Rating of perceived exertion during graded incremental wheelchair propulsion exercise.]

For participant A, the exponential-shaped BLa curve alone presented challenges in threshold identification, although the BLa increase seemed to accelerate at the third or fourth stage with the BLa increase rate over 0.9 points. The $\dot{V}E$ plot also suggested potential inflection points at the third or fourth stage with the $\dot{V}E$ increase rate over 7.8 points. The $\%\dot{V}O_{2peak}$, $\%PR_{peak}$, and RPE at the fourth stage (79.2%, 90.3%, and 16) were found to be comparable with the literature values. These data supported designating the fourth stage as LT2. For participant B, LT2 was determined based on a clear lactate inflection at the fourth stage with the BLa increase rate over 1.4 points. For participant C, who showed no clear inflection in either BLa or $\dot{V}E$, the fourth stage was suggested to be near LT2 by $\%\dot{V}O_{2peak}$ and $\%PR_{peak}$ at this stage (79.3% and 92.0%, respectively). However, as discussed below, $\dot{V}O_{2peak}$ and PR_{peak} may have been underestimated in participant C, and these results were not utilized for LT2 determination. The RPE of participant C was quite low throughout all test stages, with a maximum value of 12 at the fifth stage. Taking these findings into account, LT2 could not be explicitly determined. Therefore, the fifth stage was designated as a provisional threshold for subsequent analysis.

OBLA was determined solely based on BLa data, between the second and third stages for participants A and B, and between the first and second stages for participant C.

Table 1 presents physiological parameter comparisons between LT2 and OBLA, and

Table 2 shows peak values of BLa, $\dot{V}O_2$, PR, and race performance. In the second part of the test, participant C could not reach exhaustion due to ergometer problems; therefore, these peak values may be underestimated. Substantial discrepancies were observed between LT2 and OBLA parameters for all participants. Notably, participant C, who demonstrated the highest velocity at LT2, paradoxically recorded the lowest velocity at the OBLA.

[Table 1. Physiological parameters at LT2 and OBLA.]

[Table 2. Peak physiological parameters and race performance.]

Race performance showed positive correlation with exercise intensity at LT2 ($r = 0.92$), but negative correlation with OBLA intensity ($r = -0.77$).

Discussion

This study assessed individual lactate threshold (LT2) during wheelchair propulsion in elite wheelchair long-distance racers. All participants exhibited BLa exceeding 4 mmol/l at their LT2, and the exercise intensity relevant to LT2 was correlated with race performance, while no positive correlation was found for that relevant to OBLA.

Most previous studies in wheelchair athletes reported BLa around or below 4 mmol/l at MLSS or LT2. For example, Perret et al[23] examined MLSS of wheelchair racers in wheelchair propulsion exercise and found BLa at MLSS to be approximately 4.1 mmol/l. Leicht et al[18] reported LT2 (referred to as AT in their article) and RCP of wheelchair rugby and basketball athletes in wheelchair propulsion exercise to be 2.48 and 3.57 mmol/l, respectively. In contrast, this study demonstrated that elite wheelchair racers have substantially higher BLa at LT2 (5.8 to 7.7 mmol/l). This elevated BLa may be related to the physiological characteristics of our elite participants.

The physiological parameters relevant to LT2 were examined to validate the LT2 assessment. The %$\dot{V}O_{2peak}$ at LT2 in participant A was comparable to literature values obtained from wheelchair athletes (around 76-78% at MLSS, LT2 or RCP),[18,23] which also supported the LT2 determination. For participant C, the %$\dot{V}O_{2peak}$ at LT2 was slightly higher than these values, possibly due to $\dot{V}O_{2peak}$ underestimation. The %PR_{peak} at LT2 was comparable to literature values in all participants (around 92% of heart rate max at MLSS),[23] although participant C's values may have been affected by PR_{peak} underestimation. In participants A and B, the RPE at LT2 was comparable to literature values (15-16).[18,23] However, the lower RPE in participant C suggests that LT2 may be higher than the fifth stage.

Another widely-used objective and practical approach for MLSS assessment is the fixed BLa method, particularly with a threshold of 4 mmol/l (OBLA). However, our results raise concerns about its practicality in wheelchair propulsion exercise. OBLA occurred at significantly lower intensities than LT2, with its relevant physiological parameters falling below literature values. This indicates that OBLA substantially underestimated MLSS. Our findings suggest that the OBLA method should not be applied to wheelchair propulsion exercises.

Despite the limited sample size, the observed relationship between LT2 exercise intensity and race performance suggests that lactate thresholds may still be important performance determinants in wheelchair racing, as in other endurance sports. Conversely, OBLA intensity showed no positive relationship with race performance, implying its inability to assess the threshold appropriately. For LT2, it was noteworthy that its intensity (26.3-28.3 km/h) was consistently lower than actual average race velocity (28.7-30.2 km/h). This difference can be attributed to the tactical aspects of wheelchair racing. During races, racers frequently draft behind competitors or adopt aerodynamic positions that substantially reduce drag resistance and power output requirements. This suggests that wheelchair racers compete at higher velocities than they could achieve alone with continuous propulsion. Despite this difference between LT2 and race performance, the velocity at LT2 serves as a useful indicator of wheelchair racers' capability.

Several limitations should be acknowledged. First, the small sample size limits the generalizability of our findings. While high BLa at LT2 was notably observed in elite wheelchair racers, it remains unclear whether this occurs in sub-elite racers. Further research with larger sample sizes is needed to establish more robust statistics for physiological parameters at LT2 and better elucidate the relationship between LT2 intensity and race performance. Second, the graded incremental exercise test protocol can be refined. Settings such as the number of stages and the exercise intensity progression could potentially be modified to better identify the inflection points of BLa and $\dot{V}E$. Increasing the number of stages could allow for more detailed determination of thresholds. However, this would likely increase the burden on participants. Therefore, further consideration needs to be given to protocols that balance accurate threshold assessment with practicality.

This study demonstrates that appropriate evaluation of individual LT2 during wheelchair propulsion is feasible in elite wheelchair racers. Understanding this threshold is crucial for establishing appropriate training intensities. Such assessments should be incorporated into regular training cycles to optimize athletic development. Threshold evaluation should not rely on simplified methods like OBLA but rather consider individual physiological parameters through comprehensive assessment. Additionally, coaches and racers should be cautious about using velocity as a reference parameter when applying threshold concepts to training. The power output required to maintain a specific velocity varies with several resistance factors. Consequently, velocity-based prescriptions may not accurately reflect the physiological stress imposed on racers. Instead, PR or heart rate would offer more reliable parameters for training intensity control. Regular LT2 assessments should be conducted to monitor training adaptations and adjust training programs accordingly.

Conclusion

This study assessed individual LT2 during wheelchair propulsion exercise in elite wheelchair racers and found high BLa at this threshold (5.8-7.7 mmol/l). These elevated BLa likely reflect the characteristics of our elite participants. The physiological parameters at LT2 were consistent with previous literature values, supporting the validity of our LT2 determination. The findings suggest that the fixed BLa of 4 mmol/l (OBLA) might be inappropriate for threshold assessment in wheelchair propulsion exercises, as it substantially underestimates MLSS. While the small sample size limits the generalizability of the findings, the observed relationship between LT2 intensity and race performance suggests that the lactate threshold may be important determinants of performance in wheelchair racing. These findings provide practical implications for training prescription and monitoring for wheelchair racers, emphasizing the importance of individual LT2 assessment.

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Contributions

Conceptualization: TM; Methodology: TM, TK, TY, HG, RM, NH; Data Acquisition: TM, TK, TY, HG, RM, YT, NH; Formal analysis and investigation: TM, TK, TY, HG, RM; Writing - original draft preparation: TM; Writing - review and editing: TM, TK, TY, HG, RM, YT, NH.

Disclosure of Interest

The authors report no conflict of interest.

References

1. Billat VL, Sirvent P, Py G, Koralsztein JP, Mercier J. The concept of maximal lactate steady state: a bridge between biochemistry, physiology and sport science. *Sports Med.* 2003; 33(6): 407-426.
2. Urhausen A, Coen B, Weiler B, et al. Individual anaerobic threshold and maximum lactate steady state. *Int J Sports Med.* 1993; 14(3): 134-139.
3. Beneke R. Anaerobic threshold, individual anaerobic threshold, and maximal lactate steady state in rowing. *Med Sci Sports Exerc.* 1995; 27(6): 863-867.
4. Stegmann H, Kindermann W, Schnabel A. Lactate kinetics and individual anaerobic threshold. *Int J Sports Med.* 1981; 2(3): 160-165.
5. Ahmaidi S, Hardy JM, Varray A, Collomp K, Mercier J, Préfaut C. Respiratory gas exchange indices used to detect the blood lactate accumulation threshold during an incremental exercise test in young athletes. *Eur J Appl Physiol Occup Physiol.* 1993; 66(1): 31-36.
6. Hofmann P, Bunc V, Leitner H, Pokan R, Gaisl G. Heart rate threshold related to lactate turn point and steady-state exercise on a cycle ergometer. *Eur J Appl Physiol Occup Physiol.* 1994; 69(2): 132-139.

7. Smith CG, Jones AM. The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. *Eur J Appl Physiol.* 2001; 85(1-2): 19-26.
8. McLellan TM. Ventilatory and plasma lactate response with different exercise protocols: a comparison of methods. *Int J Sports Med.* 1985; 6(1): 30-35.
9. Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol (1985).* 1986; 60(6): 2020-2027.
10. Dickhuth HH, Yin L, Niess A, Röcker K, Mayer F, Heitkamp HC, Horstmann T. Ventilatory, lactate-derived and catecholamine thresholds during incremental treadmill running: relationship and reproducibility. *Int J Sports Med.* 1999; 20(2): 122-127.
11. Cheng B, Kuipers H, Snyder AC, Keizer HA, Jeukendrup A, Hesselink M. A new approach for the determination of ventilatory and lactate thresholds. *Int J Sports Med.* 1992; 13(7): 518-522.
12. Sjödin B, Jacobs I. Onset of blood lactate accumulation and marathon running performance. *Int J Sports Med.* 1981; 2(1): 23-26.
13. Heck H, Mader A, Hess G, Mücke S, Müller R, Hollmann W. Justification of the 4-mmol/l lactate threshold. *Int J Sports Med.* 1985; 6(3): 117-130.
14. Harnish CR, Swensen TC, Pate RR. Methods for estimating the maximal lactate steady state in trained cyclists. *Med Sci Sports Exerc.* 2001; 33(6): 1052-1055.

15. Schmid A, Huonker M, Aramendi JF, Klüppel E, Barturen JM, Grathwohl D, Schmidt-Trucksäss A, Berg A, Keul J. Heart rate deflection compared to 4 $mmol \cdot l^{-1}$ lactate threshold during incremental exercise and to lactate during steady-state exercise on an arm-cranking ergometer in paraplegic athletes. *Eur J Appl Physiol Occup Physiol.* 1998; 78(2): 177-182.

16. Beneke R, Leithauser RM, Hutler M. Dependence of the maximal lactate steady state on the motor pattern of exercise. *Br J Sports Med.* 2001; 35(3): 192-196.

17. Otto AK, Reer R, Holtfreter B, Riepenhof H, Schröder J. Physiological responses at the anaerobic threshold and at peak performance during arm crank ergometer diagnostics compared to wheelchair propulsion on a treadmill in elite wheelchair basketball players. *Sport Orthop Traumatol.* 2019; 35(1): 49-55.

18. Leicht CA, Griggs KE, Lavin J, Tolfrey K, Goosey-Tolfrey VL. Blood lactate and ventilatory thresholds in wheelchair athletes with tetraplegia and paraplegia. *Eur J Appl Physiol.* 2014; 114(8): 1635-1643.

19. Lakomy HK, Campbell I, Williams C. Treadmill performance and selected physiological characteristics of wheelchair athletes. *Br J Sports Med.* 1987; 21(3): 130-133.

20. Rotstein A, Sagiv M, Ben-Sira D, Werber G, Hutzler J, Annenburg H. Aerobic capacity and anaerobic threshold of wheelchair basketball players. *Paraplegia.* 1994; 32(3): 196-201.

21. Coutts KD, McKenzie DC. Ventilatory thresholds during wheelchair exercise in individuals with spinal cord injuries. *Paraplegia.* 1995; 33(7): 419-422.
22. Vinet A, Le Gallais D, Bernard PL, et al. Aerobic metabolism and cardioventilatory responses in paraplegic athletes during an incremental wheelchair exercise. *Eur J Appl Physiol Occup Physiol.* 1997; 76(5): 455-461.
23. Perret C, Labruyère R, Mueller G, Strupler M. Correlation of heart rate at lactate minimum and maximal lactate steady state in wheelchair-racing athletes. *Spinal Cord.* 2012; 50(1): 33-36.
24. de Klerk R, Vegter RJK, Veeger HEJ, van der Woude LHV. Technical note: a novel servo-driven dual-roller handrim wheelchair ergometer. *IEEE Trans Neural Syst Rehabil Eng.* 2020; 28(4): 1-9.
25. Fuss FK. Influence of mass on the speed of wheelchair racing. *Sports Eng.* 2009; 12, 41-53.
26. Gross AC, Kyle CR, Malewicki DJ. The aerodynamics of human-powered land vehicles. *Sci Am.* 1983; 249(6): 142-152.
27. Hennekam W. The speed of a cyclist. *Phys Educ.* 1990; 25(3): 141-146.
28. Akashi K, Yamanobe K, Shirasaki K, Miyazaki Y, Mitsui T. Influence of driving posture and driving velocity on wind drag while traveling on flat land and a downward slope in

the wheelchair marathon: Wind tunnel experiment and driving simulation. *Jpn J Phys Educ Health Sport Sci.* 2019; 64(1): 67-77.

29. Borg G. Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med.* 1970; 2(2): 92-98.

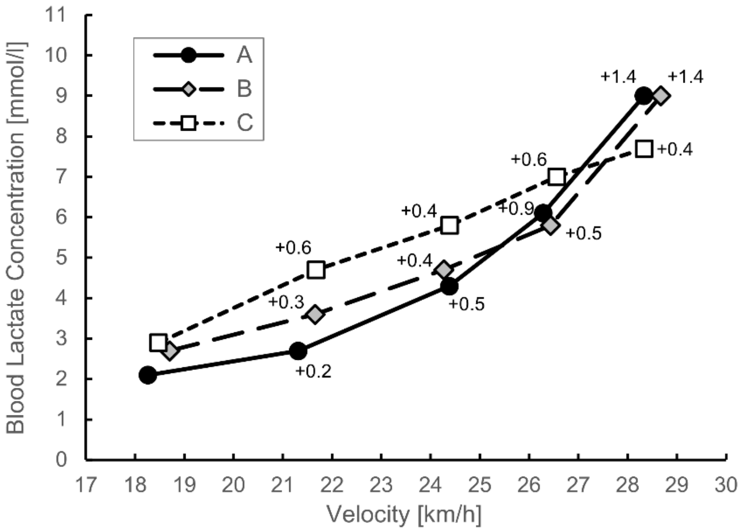

Figure 1. Changes in blood lactate concentration during graded incremental wheelchair propulsion exercise.

Numbers adjacent to plots indicate rate of increase from previous stage (mmol/l per km/h).

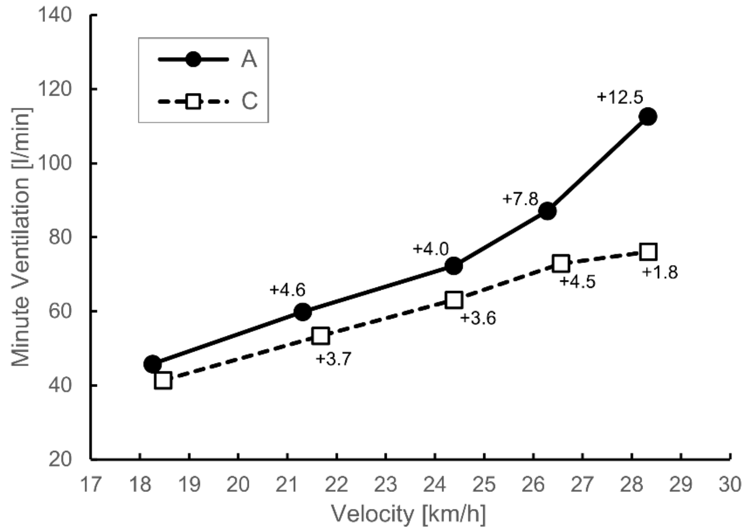

Figure 2. Changes in minute ventilation during graded incremental wheelchair propulsion exercise.

Numbers adjacent to plots indicate rate of increase from previous stage (l/min per km/h).

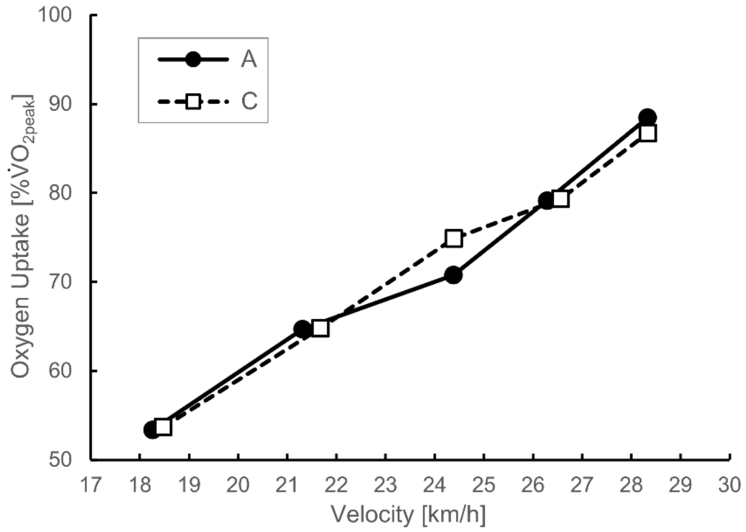

Figure 3. Oxygen uptake during graded incremental wheelchair propulsion exercise.

Values are expressed as $\%\dot{V}O_{2peak}$.

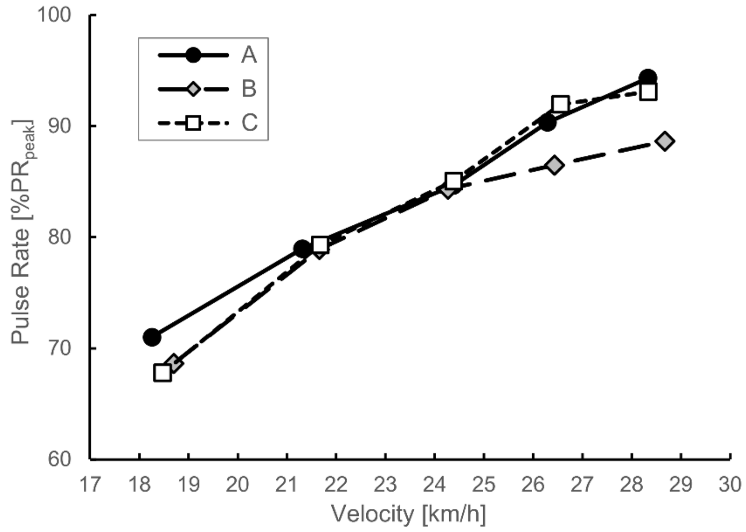

Figure 4. Pulse rate response during graded incremental wheelchair propulsion exercise.

Values are expressed as %PR$_{peak}$.

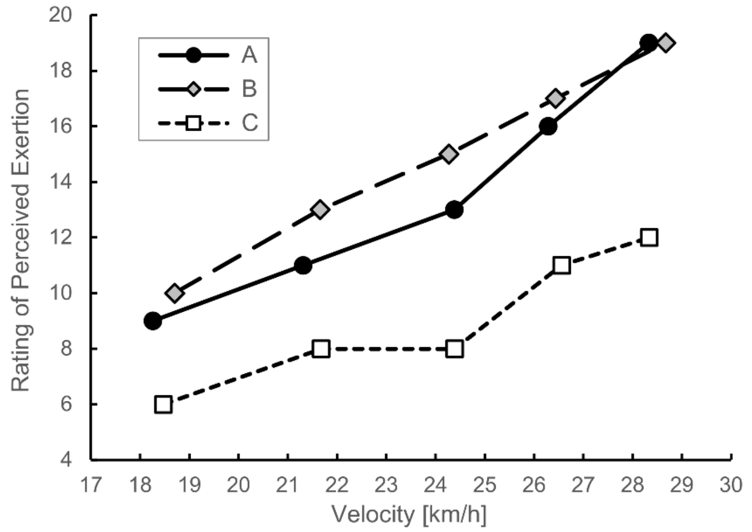

Figure 5. Rating of perceived exertion during graded incremental wheelchair propulsion exercise.

Table 1. Physiological parameters at LT2 and OBLA.

Threshold	Participant	BLa [mmol/l]	$\dot{V}O_2$ [ml/min/kg]	$\%\dot{V}O_{2peak}$ [%]	PR [bpm]	$\%PR_{peak}$ [%]	RPE	Velocity [km/h]
LT2	A	6.1	40.6	79.2	159	90.3	16	26.3
	B	5.8	-	-	160	86.5	17	26.4
	C	7.7	40.8	86.7	162	93.1	12	28.3
OBLA	A	4.0	35.7	69.6	147	83.6	12.6	23.8
	B	4.0	-	-	150	80.9	13.7	22.6
	C	4.0	28.4	60.5	130	74.8	7.2	20.4

Table 2. Peak physiological parameters and race performance.

Participant	Physiological Peak			Race Performance
	BLa_{peak} [mmol/l]	$\dot{V}O_{2peak}$ [ml/min/kg]	PR_{peak} [bpm]	Average Velocity [km/h]
A	16.4	51.2	176	29.2
B	12.5	50.8	184	28.7
C	8.6	47.0	174	30.2