american physiological society®

JOURNAL OF APPLIED PHYSIOLOGY®

J Appl Physiol 135: 1415–1420, 2023.
First published November 2, 2023; doi:10.1152/japplphysiol.00698.2023

SHORT REPORT

Aging and Adaptation to Exercise

Physiological characteristics of a 92-yr-old four-time world champion indoor rower

Lorcan S. Daly,[1,2,3] Bas Van Hooren,[4] and Philip Jakeman[5]

[1]*Department of Sport and Health Sciences, Technological University of the Shannon: Midlands Midwest, Athlone, Ireland;* [2]*SHE Research Group, Technological University of the Shannon: Midlands Midwest, Athlone, Ireland;* [3]*Sport and Human Performance Research Centre, University of Limerick, Limerick, Ireland;* [4]*Department of Nutrition and Movement Sciences, NUTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre+, Maastricht, The Netherlands; and* [5]*Department of Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland*

Abstract

This study assessed the physiological, performance, nutritional intake, and training characteristics of a 92-yr-old four-time master world champion indoor male rower. Body composition was assessed via bioelectrical impedance. Oxygen uptake, carbon dioxide production, ventilation, and heart rate were measured at rest and during a 2,000-m time trial on a rowing ergometer. Maximal power was assessed to compute anaerobic power reserve. Training included ≈ 30 km/wk on the rowing ergometer. Herein, 70% of distances were covered at light intensities (RPE, 10–12), 20% at hard (RPE, 13–17), and 10% at near maximal or maximal (RPE, 17–20). Resistance training was performed during ≈ 2 sessions/wk, and involved three sets of dumbbell lunges, rows, and curls, respectively, taken close (or to) failure. Dietary intake was high in protein [2.3 ± 0.1 g·kg^{-1} lean body mass (LBM)], conferring a caloric intake of 33.4 ± 1.7 kcal·kg^{-1} LBM. The participant demonstrated muscle mass of 47.7 kg, fat mass of 9.1 kg (15.4% body fat), forced vital capacity of 3.36 L, time constant (τ) to steady state of 30.2 s, peak relative oxygen pulse of 0.18 ([mL·O_2/beats/min]/kg), peak heart rate of 153 beats/min, and maximum power of 220 W (140 W anaerobic power reserve). This 92-yr-old athlete demonstrated remarkably fast oxygen uptake kinetics, akin to values for a healthy young adult, indicating well-developed and/or maintained cardiopulmonary function. The high values for cardiopulmonary function, muscle mass, metabolic efficiency, and maximum power output may infer the pliability of these systems to maintain high functionality at an advanced age.

NEW & NOTEWORTHY To our knowledge, this study is the first to characterize the physiological attributes of a competitive rower (4-time master world champion) at an advanced age (≥ 85 yr). The participant demonstrated a high muscle mass (47.7 kg; 80.6% body mass), maximal power (220 W), and exceptional oxygen uptake kinetics (τ of 30.2 s), similar to values reported for healthy young adults.

aging; master athlete; oxygen kinetics; physiology

INTRODUCTION

Master athletes of advanced ages (≥80 yr) who perform at a world-class level represent a unique population providing valuable insights into the capacity of humans to cultivate and retain high levels of physiological function (1–3) that exemplify a healthy aging philosophy (1, 2, 4). This paradigm may be particularly fitting to the determinants of rowing, for example, aerobic function, muscular power, and metabolic thresholds (2, 5), and the subsequent multifactorial physiological adaptations conferred by training for the sport (1, 5).

Notable studies to date have demonstrated that master athlete possesses physiological attributes that are superior to age-matched sedentary individuals (6, 7). Although causality may not be established, the data reinforces the supposition that training in later life appears to capitalize on the plasticity of the physiological systems challenged during endurance exercise, thereby stimulating, preserving, and realizing a high-level functionality (5, 6).

Maximal oxygen consumption and oxygen uptake kinetics are markers of cardiorespiratory fitness that underpin rowing performance (2, 5). Other physiological characteristics, such as the capability of the neuromuscular system to produce mechanical power and the glycolytic and phosphagen metabolic systems to produce energy, are also associated with rowing performance (2, 8). Nevertheless, studies in advanced-age populations remain scant, with data from master athletes >90 yr of age rarer still (5, 9).

Ultimately, an integrated understanding of master athletes' physiology, and the practices they apply to maintain

Correspondence: L. S. Daly (lorcan.daly@tus.ie).
Submitted 29 September 2023 / Revised 23 October 2023 / Accepted 25 October 2023

8750-7587/23 Copyright © 2023 the American Physiological Society.

Downloaded from journals.physiology.org/journal/jappl (084.088.141.041) on January 19, 2024.

such high levels of physiological function, would elicit novel insight and yield applicable information (1–3). To contribute to the knowledge base, this study examined the physiological, performance, nutritional, and training characteristics of a 92-yr-old four-time master world champion indoor rower.

MATERIALS AND METHODS

Ethical approval was granted by the University of Limerick Faculty of Education and Health Sciences research ethics committee (Code: 2023_03_05_EHS).

Participant

Richard Morgan (RM) is a lightweight (−75 kg) 2,000-m 92-yr-old master indoor rower and four-time world champion (winning in 2007, 2017, 2021, and 2022). Of note, RM started rowing at 73 yr of age and before this did not undertake any structured training or exercise. Prior to retirement, RM started his career as a baker, later working as a chemical operator in Ireland and Japan. Presently, RM resides in Ireland with his family.

Training Regimen

The training regimen undertaken by RM for his ≈20 yr engagement in rowing could be described as pyramidal and concurrent. On average, RM completed 1,000–1,500 km/yr (≈30 km/wk; 40 min/day) on the rowing ergometer, supplemented with 2–3 days/wk of resistance training. Remarkably, RM remained uninjured for the entirety of his rowing career.

Dietary Intake

The participant reported having an extremely consistent diet throughout his ≈20-yr career. A 4-day dietary recall using the European Prospective Investigation of Cancer food diary provided an estimate of habitual dietary intake (10). Macronutrient composition and energy intake were determined using proprietary software (Nutritics, Ireland).

Testing Procedures

Testing was completed 3 h postprandial, and the participant arrived at the laboratory well-rested.

Anthropometry and body composition.

Height and body mass were measured using a stadiometer (Seca 216 stadiometer, Germany), and body composition was assessed via multifrequency bioelectrical impedance analysis (Tanita BC 418) as per the manufacturer's instructions (11).

Cardiopulmonary, metabolic, and power output measurements.

Cardiopulmonary and metabolic measurement at rest and exercise employed a gas exchange and pulmonary function analysis system (Ultima CardiO_2 System; Med graphics). Rate of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$), minute ventilation ($\dot{V}E$), and respiratory frequency were recorded throughout (8, 12) and interpreted using 30-s rolling averages. Heart rate was monitored using a Polar H10 chest strap (Polar, Finland).

Pulmonary function. A flow-volume loop of maximal inspiration and expiration was completed, with the best of three attempts recorded.

Resting metabolic rate. Following 20 min at rest, a face mask (Hans Rudolph) was placed over the mouth and nose. Expired gas was captured using an indirect calorimeter for 10 min at rest.

Maximal peak power output. The participant performed a 5-min warm-up with a rowing ergometer (Concept 2) at a self-selected pace of 75 W. After 3 min rest, the participant performed six "introductory" and six "all-out" strokes at the same resistance to determine maximum power (13).

Metabolic testing during exercise. A 2,000-m rowing time trial was completed. The participant was seated at rest for 2 min before the trial commenced and the flywheel remained still. The participant initiated a square change in power, approximating race pace, as is his typical tactical behavior during competition. A square change in power is also necessary for the assessment of transient oxygen uptake kinetics (14, 15).

Data Analyses

Oxygen uptake kinetics was evaluated as a monoexponential function using a nonlinear regression method previously applied to elite rowers (14).

The rate of energy expenditure (EE), fat oxidation (FAT_{ox}), and carbohydrate (CHO_{ox}) oxidation were calculated as per Jeukendrup and Wallis (16). The training EE and metabolic equivalent of task (MET) were calculated as per Ainsworth and colleagues (17). Gross (e_{gross}) and net (e_{net}) metabolic efficiency were computed using the methods employed by Jensen and colleagues (18). O_2 pulse and relative O_2 pulse were calculated as described by Billat and colleagues (9). Anaerobic power reserve was computed as per Sandford and colleagues (19).

Data analysis and visualization were performed using RStudio (version 4.1.0, RStudio) and GraphPad Prism (version 8, GraphPad Software), respectively.

RESULTS

This projects' raw data are openly accessible via the following link (https://rb.gy/3kzbz).

The participant's *1*) historical best performances at each age category of the 2,000-m lightweight (−75 kg) division world championships, *2*) anthropometry, *3*) body composition, and *4*) pulmonary function are presented in Table 1.

The participant's physiological measures can be seen in Fig. 1, oxygen uptake kinetics in Fig. 2, and metabolic measurements can be seen in Table 2.

Oxygen uptake kinetics in the transition from rest to steady-state rowing are presented in Fig. 2. A time constant (τ) of 30.2 s and amplitude of 1,032 $mL \cdot min^{-1}$ was recorded resulting in an oxygen deficit of 1.0 L before attainment of a steady-state $\dot{V}O_2$ of ≈1,250 $mL \cdot min^{-1}$. The cardiodynamic phase time delay was 38.9 s.

DISCUSSION

This study outlines the physiological and performance characteristics of a 92-yr-old four-time master world champion indoor rower. To the authors' knowledge, this is the first analysis of a competitive rower of an advanced age.

Downloaded from journals.physiology.org/journal/jappl (084.088.141.041) on January 19, 2024.

Table 1. *Participant's performance, anthropometry, body composition, lung function, nutritional intake, and estimated energy expenditure*

LW (−75 kg) 2,000 m Performance	WC Best, s	World Record, s	Change (%) from −79
Senior adult category		356	
Sub-79 age category	479.6	444	
Sub-84 age category	515.1	460.4	−3.7%
Sub-89 age category	516	493.6	−11.2%
Sub-94 age category	589.9	524.9	−18.2%
Anthropometry	**Value**		
Height, cm	162		
Body mass, kg	59.2		
Body Composition	**kg**	**% BM**	**Percentile Score**
Fat-free mass	50.2	84.8	95th (70–79 yr)
Muscle mass	47.7	80.6	
Body fat	9.1	15.4	95th (70–79 yr)
Bone mass	2.5	4.2	
Lung Capacity Measurement	**Value**	**% Pred**	
Forced vital capacity (FVC, L)	3.36	119	
Forced expiratory volume in 1 s (FEV_1)	2.52	121	
Ratio of forced expiratory volume in 1 s to forced vital capacity (FEV_1%)	78	74	
Peak expiratory flow (PEF, $L.s^{-1}$)	2.8	65	
Energy Intake	**$kcal \cdot kg^{-1}$ BM**	**$kcal \cdot kg^{-1}$ LBM**	**Recommendations**
Calories	28.4 ± 1.4	33.4 ± 1.7	>30 $kcal \cdot kg^{-1}$ LBM
Macronutrient Intake	**$g \cdot kg^{-1}$ BM**	**$g \cdot kg^{-1}$ LBM**	
Carbohydrate	3.8 ± 0.2	4.2 ± 0.3	4–6 $g \cdot kg^{-1}$ BM
Protein	1.9 ± 0.1	2.3 ± 0.1	2 $g \cdot kg^{-1}$ BM
Fat	0.7 ± 0.1	0.8 ± 0.1	1–1.5 $g \cdot kg^{-1}$ BM
Estimated Energy Expenditure	**$kcal \cdot kg^{-1}$ BM**	**$kcal \cdot kg^{-1}$ LBM**	
Resting metabolism	20.4	24.0	
Activities of daily living (20)	4.1	4.8	
Thermic effect of food	2.8	3.3	
LI rowing training (≈ 4 METs 35 min/day)	2.0	2.3	
HI rowing training (≈ 7 METs 5 min/day)	0.5	0.6	
Resistance training (≈ 5 METs 10 min/day)	0.7	0.8	
Total estimated energy expenditure	30.5	35.8	

BM, body mass; LBM, lean body mass; LW, lightweight; MET, metabolic equivalent of task; Pred, predicted; WC, world championship. Lung capacity predicted values were derived from global lung function equation (26); body composition percentile values were obtained from the American College of Sports Medicine tables (32); dietary recommendations were obtained from Louis and colleagues (31); MET calculations for obtained from Ainsworth et al. (17); thermic effect of food calculated in line with recommendations from de Jonee et al. (33); activities of daily living calculated in line with recommendations from Tremblay et al. (34).

Foremost, the participant demonstrated notably fast oxygen uptake kinetics (τ of 30.2 s), which is similar to a mean value of 30 ± 10 s for master endurance athletes 66–85 yr of age (20) and young healthy individuals ≈25 yr of age (15), but greater than twofold the mean 13.4 ± 4 s reported for Olympic medal caliber rowers (14). This finding serves as a proxy indicator of a well-developed aerobic function and may, in part, be associated with possible training adaptations (e.g., enhanced stroke volume, mitochondrial function/density, hemoglobin levels, or angiogenesis) (5, 14, 15). Moreover, the capacity to rapidly increase oxygen transport and utilization at the start of exercise is an important determinant of endurance performance (i.e., sparing endogenous high-energy phosphagen and glycolytic fuel reserves) (14, 15). Though the magnitude of age-induced decline of cardiorespiratory function may exponentiate (2, 5), the present observations support the contention that this may be countered by a sufficient adaptive stimulus (7). In parallel, supportive and adaptive peripheral metabolic capacity (for instance, muscular oxidative enzyme activity [citrate synthase and β-hydroxy-acid dehydrogenase]) is reported to be higher in octogenarians engaged in lifelong endurance training compared with age-matched untrained counterparts (4), and mechanisms such as these could have contributed to the rapid $\dot{V}O_2$ kinetics presently observed. Indeed, appreciably accelerated $\dot{V}O_2$ kinetics have been demonstrated in older individuals (77 ± 7 yr) following training, wherein maximal citrate synthase activity increased without changes in O_2 delivery, implying the former adaptation may be more responsive to training and possibly a key contributor to the $\dot{V}O_2$ kinetics currently reported. Also noteworthy, the participant's $\dot{V}O_{2peak}$ was 10.8% higher than sedentary octogenarians and 47.8% lower than octogenarians engaged in lifelong endurance training who were, on average, 11 yr his junior (4). Although longitudinal data was unavailable, the participant's unique training history (i.e., commencing training at 73 yr of age) lends support to the premise that aerobic function remains malleable/plastic and may be robustly moderated with appropriate exercise stimuli (5, 6), even without significant development in younger years.

Downloaded from journals.physiology.org/journal/jappl (084.088.141.041) on January 19, 2024.

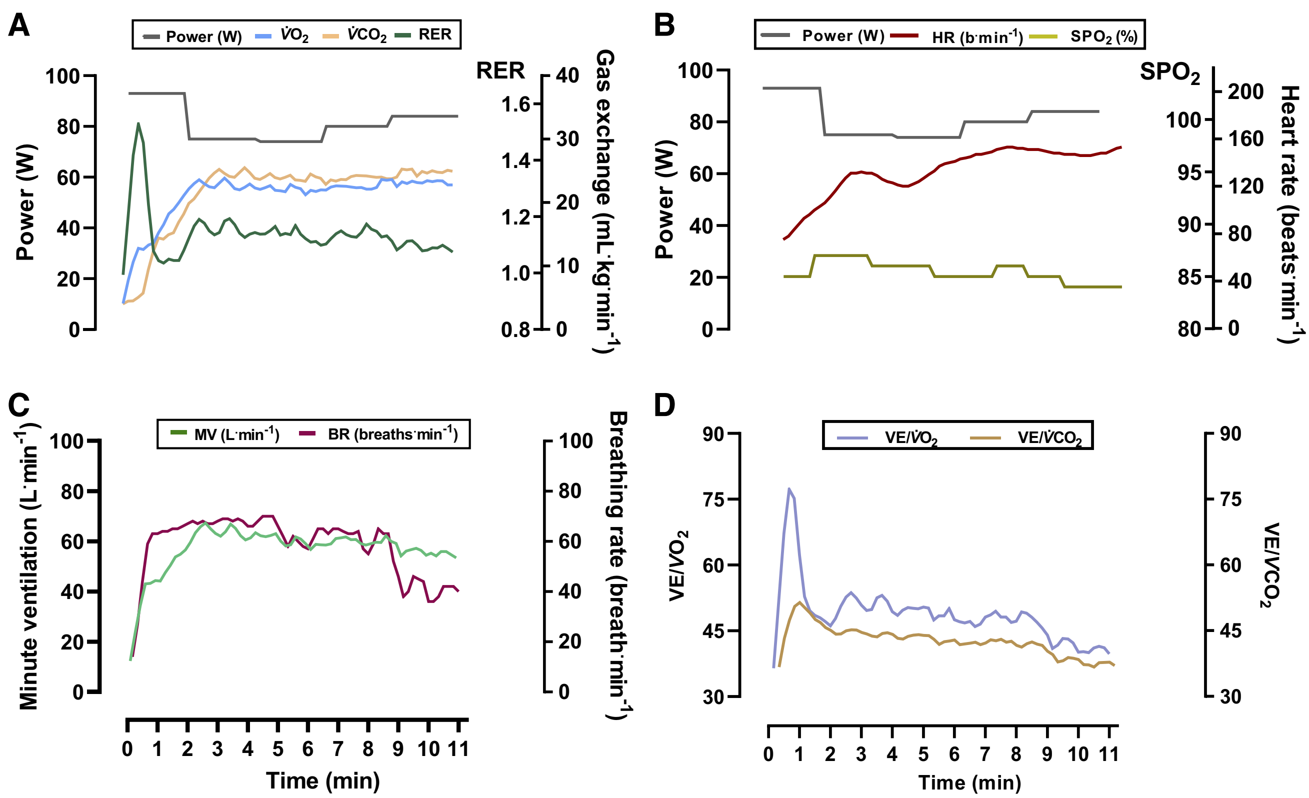

Figure 1. Physiological outcomes recorded during the exercise test. Relative $\dot{V}O_2$ and $\dot{V}CO_2$ (relative to body mass) and power (*A*), heart rate and power (*B*), minute ventilation and respirator rate (*C*), and respiratory exchange ratio and peripheral oxygen saturation (*D*). BR, breathing rate; HR, heart rate; RER, respiratory exchange ratio; SpO_2, peripheral oxygen saturation; $\dot{V}E$, minute ventilation. $\dot{V}CO_2$, carbon dioxide production; $\dot{V}O_2$, oxygen uptake.

Noteworthy, the participant demonstrated a high peak relative oxygen pulse (relative O_{2pulse}) of 0.18 mL·beats/min/kg, a predictive indicator of health and cardiorespiratory function (8, 9), which could be underpinned by a number of mechanisms, for example, blood volume expansion and enhanced cardiac preload/contractility (1, 3). This value was 33% above predicted maximums for a healthy untrained 80-yr-old (21) and 67% lower than a 75-yr-old master world record-holding marathon runner (22). Compared with competitive rowers, peak relative O_{2pulse} during the trial was ≈55% lower than the maximum values reported for young Olympic champions, who underwent annual physiological assessments from 16 to 27 (23) and 19 to 40 yr of age (8). Indeed, O_{2pulse} constitutes an indirect marker of stroke volume, and maximal values typically approximate 0.25 mL·beats/min/kg in well-trained young endurance athletes (3), declining to ≈0.18 mL·beats/min/kg in master athletes at 70 yr of age (24). Nevertheless, prior work demonstrated remarkable values (0.27 mL·beats/min/kg) for a centenarian cyclist (9). Collectively, these findings suggest age-related decrements in O_{2pulse} can be mitigated by a continuation of training into later years (5, 8, 9).

During the current 2,000-m trial, peak HR reached 153 beats/min, 10 beats higher than the predicted maximum from the Tanaka equation (208 − 0.7 × age) (1) and 25 beats higher than the Fox equation (220 − age) (25). With respect to pulmonary capacity, the participant demonstrated an FVC corresponding to 119% and FEV_1 of 121% of the age-predicted norms, respectively (26). In contrast, peak expiratory flow (2.9 L·s^{-1}) was 65% of predicted values (26). It is possible this may, in part, be explained by age-dependent losses of elastic recoil, as reported for older active ($\dot{V}O_{2max}$ [44 ± 2 mL·kg·min^{-1}) participants (27). The comparably lower peak flow capacity may help to explain the high average RER values and could constitute a performance limitation by increasing the metabolic cost of breathing during intense exercise (27).

A trial average e_{gross} value of 15.5% was comparable with a former Olympic champion rower (18.7%) (8) and well-trained young female rowers (19.7%) (28) undertaking similar trials, implying a relatively well-developed and/or preserved metabolic efficiency. It is possible that consistent training spanning a lengthy career (possibly developing efficient motor control) and high maximal power capacity (220 W) may be contributary factors undergirding the current e_{gross} values (8, 19). Certainly, it is reasonable to speculate this high mechanical power may be underpinned in part by morphological characteristics (muscle mass: 47.7 kg; 80.6% of body mass), in addition to possible neural and technical factors that may have been refined during training. Undoubtedly, the training and nutritional practices reported presently, particularly the completion of intense resistance exercises and provision of a large amount of protein (1.9 ± 0.1 g·kg^{-1} BM [2.3 ± 0.1 g·kg^{-1} LBM], 12%–58% beyond minimum recommended intakes (29, 30), was notable. Collectively, these dietary and training practices have plausibly elicited protection against the neuro- and myogenic degenerative mechanisms of sarcopenia (1, 6), thereby possibly contributing to the morphological and mechanical properties exhibited (1, 31).

The analysis is not without limitations, the principal of which may be the absence of longitudinal physiological data.

Downloaded from journals.physiology.org/journal/jappl (084.088.141.041) on January 19, 2024.

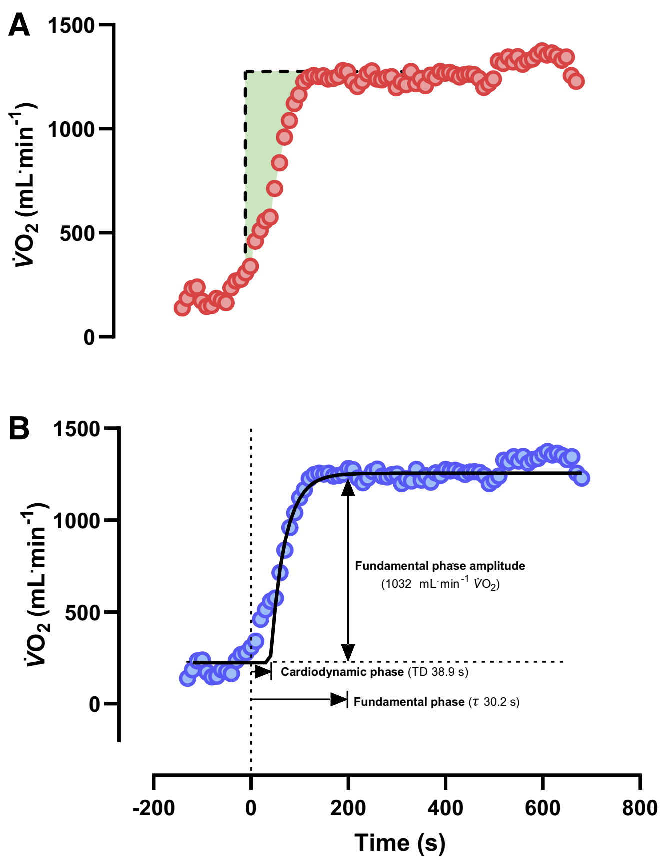

Figure 2. Oxygen uptake kinetics in the transition from rest to exercise (at 0 s, trial cessation at 652 s). Oxygen deficit can be seen in *A* and the monoexponential model (95% CI; 5.2 s) overlayed on the raw data can be seen in *B*.

The provision of additional variables, such as muscle fiber typology and oxidative enzyme activity would also provide valuable context. Finally, although the exercise protocol undertaken provided unique insight, an incremental protocol would have provided other useful results (e.g., FAToxpeak).

Conclusions

The current analysis demonstrates novel findings. The principal observation relates to the kinetics of oxygen uptake that were found to be similar to those reported for healthy young adults (15). This is a remarkable finding in a 92-yr-old and may serve to highlight the plasticity of cardiopulmonary and respiratory functional capacity, even in persons of advanced age, when supported by sufficient exercise stimulus. Moreover, well-developed physiological characteristics, i.e., pulmonary function, $\dot{V}O_{2peak}$, O_{2pulse}, maximum power, and e_{gross}, were observed, providing further support to the premise that exercise training may counteract aging-dependent impairments across a range of systems. Finally, the training and nutritional practices of this athlete are also outlined and may confer valuable insights for researchers and practitioners within the domain.

DATA AVAILABILITY

The data supporting the findings of this study are openly available at https://rb.gy/3kzbz to help ensure transparency and reproducibility of the results. Researchers interested in accessing and utilizing the data are encouraged to visit the above database and contact the lead author should further information be required.

SUPPLEMENTAL DATA

The supplemental data supporting the current results are available at https://rb.gy/3kzbz.

ACKNOWLEDGMENTS

The authors sincerely thank Richard Morgan for his interest, cooperation, and commitment during this project. We also sincerely thank Stephen Clothier for assistance during preparation and testing.

GRANTS

This research project did not receive any underpinning funding.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

Table 2. *Participant's metabolic measurements during rest and exercise*

Measure	Value
Rest	
$\dot{V}O_2$, mL·min^{-1}	165.2
$\dot{V}CO_2$, mL·min^{-1}	136.3
Relative $\dot{V}O_2$, mL·kg·min^{-1}	2.8
Relative $\dot{V}CO_2$, mL·kg·min^{-1}	2.3
Ventilation ($\dot{V}E_{STPD}$ [L·min^{-1}])	5.7
RER	0.84
Energy expenditure, kcal/day	1,153.8
Carbohydrate oxidation, g·min^{-1}	0.08
Fat oxidation, g·min^{-1}	0.05
Percentage of energy derived from fat oxidation	59%
Percentage of energy derived from carbohydrate oxidation	41%
Exercise (average values during 2,000 m trial)	
$\dot{V}O_2$, mL·min^{-1}	1,264.5
$\dot{V}O_2$, mL·min^{-1}	1,434.4
Relative $\dot{V}O_2$, mL·kg·min^{-1}	21.4
Relative $\dot{V}CO_2$, mL·kg·min^{-1}	24.2
Ventilation ($\dot{V}E_{STPD}$ [L·min^{-1}])	59.1
RER	1.14
Energy expenditure, kcal·min^{-1}	7.5
Total energy expenditure, kcal	81.2
Average heart rate, beats/min	137
Oxygen pulse, mL·O_2/beats/min	9.2
Oxygen pulse, (mL·O_2/beats/min)/kg	0.16
Gross metabolic efficiency, %	15.5
Net metabolic efficiency, %	17.8
Exercise (peak values during 2,000 m trial)	
$\dot{V}O_2$, mL·min^{-1}	1,264.5
$\dot{V}CO_2$, mL·min^{-1}	1,434.4
Relative $\dot{V}O_2$, mL·kg·min^{-1}	23.2
Relative $\dot{V}CO_2$, mL·kg·min^{-1}	25.1
Heart rate, beats/min	153
Ventilation ($\dot{V}E$ $_{STPD}$ [L·min^{-1}])	66.9
RER	1.19
Oxygen pulse, mL·O_2/beats/min	10.5
Oxygen pulse, (mL·O_2/beats/min)/kg	0.18

$\dot{V}O_2$, carbon dioxide production; $\dot{V}O_2$, oxygen uptake; RER, respiratory exchange ratio.

Downloaded from journals.physiology.org/journal/jappl (084.088.141.041) on January 19, 2024.

AUTHOR CONTRIBUTIONS

L.S.D., B.V.H., and P.J. conceived and designed research; L.S.D. and P.J. performed experiments; L.S.D. and P.J. analyzed data; L.S.D. and P.J. interpreted results of experiments; L.S.D. prepared figures; L.S.D. drafted manuscript; B.V.H. and P.J. edited and revised manuscript; L.S.D., B.V.H., and P.J. approved final version of manuscript.

REFERENCES

1. **Tanaka H**, **Tarumi T**, **Rittweger J.** Aging and physiological lessons from master athletes. *Compr Physiol* 10: 261–296, 2011. doi:10.1002/cphy.c180041.
2. **Gries KJ**, **Trappe SW.** The aging athlete: paradigm of healthy aging. *Int J Sports Med* 43: 661–678, 2022. doi:10.1055/a-1761-8481.
3. **Trappe SW**, **Costill DL**, **Vukovich M**, **Jones J**, **Melham T.** Aging among elite distance runners: a 22-yr longitudinal study. *J Appl Physiol (1985)* 80: 285–290, 1996. doi:10.1152/jappl.1996.80.1.285.
4. **Trappe S**, **Hayes E**, **Galpin A**, **Kaminsky L**, **Jemiolo B**, **Fink W**, **Trappe T**, **Jansson A**, **Gustafsson T**, **Tesch P.** New records in aerobic power among octogenarian lifelong endurance athletes. *J Appl Physiol (1985)* 114: 3–10, 2013. doi:10.1152/japplphysiol.01107.2012.
5. **Valenzuela PL**, **Maffiuletti NA**, **Joyner MJ**, **Lucia A**, **Lepers R.** Lifelong endurance exercise as a countermeasure against age-related $\dot{V}o2max$ decline: Physiological overview and insights from masters athletes. *Sports Med* 50: 703–716, 2020. doi:10.1007/s40279-019-01252-0.
6. **Skoglund E**, **Stål P**, **Lundberg TR**, **Gustafsson T**, **Tesch PA**, **Thornell L-E.** Skeletal muscle morphology, satellite cells, and oxidative profile in relation to physical function and lifelong endurance training in very old men. *J Appl Physiol (1985)* 134: 264–275, 2023. doi:10.1152/japplphysiol.00343.2022.
7. **Van Hooren B**, **Lepers R.** A physiological comparison of the new—over 70 years of age—marathon record holder and his predecessor: a case report. *Front Physiol* 14: 1122315, 2023. doi:10.3389/fphys.2023.1122315.
8. **Nybo L**, **Schmidt JF**, **Fritzdorf S**, **Nordsborg NB.** Physiological characteristics of an aging Olympic athlete. *Med Sci Sports Exerc* 46: 2132–2138, 2014. doi:10.1249/MSS.0000000000000331.
9. **Billat V**, **Dhonneur G**, **Mille-Hamard L**, **Le Moyec L**, **Momken I**, **Launay T**, **Koralsztein JP**, **Besse S.** Case studies in physiology: maximal oxygen consumption and performance in a centenarian cyclist. *J Appl Physiol (1985)* 122: 430–434, 2017. doi:10.1152/japplphysiol.00569.2016.
10. **Bingham SA**, **Gill C**, **Welch A**, **Day K**, **Cassidy A**, **Khaw K**, **Sneyd M**, **Key T**, **Roe L**, **Day N.** Comparison of dietary assessment methods in nutritional epidemiology: weighed records v. 24 h recalls, food-frequency questionnaires and estimated-diet records. *Br J Nutr* 72: 619–643, 1994. doi:10.1079/bjn19940064.
11. **Leahy S**, **O'Neill C**, **Sohun R**, **Jakeman P.** A comparison of dual energy X-ray absorptiometry and bioelectrical impedance analysis to measure total and segmental body composition in healthy young adults. *Eur J Appl Physiol* 112: 589–595, 2012. doi:10.1007/s00421-011-2010-4.
12. **Daly LS**, **Ó Catháin C**, **Kelly DT.** Does physical conditioning influence performance attenuation and recovery in gaelic football? *Int J Sports Physiol Perform* 17: 862–870, 2022. doi:10.1123/ijspp.2021-0342.
13. **Metikos B**, **Mikulic P**, **Sarabon N**, **Markovic G.** Peak power output test on a rowing ergometer: a methodological study. *J Strength Cond Res* 29: 2919–2925, 2015. doi:10.1519/JSC.0000000000000944.
14. **Ingham SA**, **Carter H**, **Whyte GP**, **Doust JH.** Comparison of the oxygen uptake kinetics of club and olympic champion rowers. *Med Sci Sports Exerc* 39: 865–871, 2007. doi:10.1249/mss.0b013e31803350c7.
15. **Goulding RP**, **Burnley M**, **Wüst RC.** How priming exercise affects oxygen uptake kinetics: from underpinning mechanisms to endurance performance. *Sports Med* 53: 959–976, 2023. doi:10.1007/s40279-023-01832-1.
16. **Jeukendrup A**, **Wallis G.** Measurement of substrate oxidation during exercise by means of gas exchange measurements. *Int J Sports Med* 26, *Suppl 1*: S28–S37, 2005. doi:10.1055/s-2004-830512.
17. **Ainsworth BE**, **Haskell WL**, **Herrmann SD**, **Meckes N**, **Bassett DR Jr**, **Tudor-Locke C**, **Greer JL**, **Vezina J**, **Whitt-Glover MC**, **Leon AS.** 2011 Compendium of Physical Activities: a second update of codes and MET values. *Med Sci Sports Exerc* 43: 1575–1581, 2011. doi:10.1249/MSS.0b013e31821ece12.
18. **Jensen RL**, **Freedson PS**, **Hamill J.** The prediction of power and efficiency during near-maximal rowing. *Eur J Appl Physiol Occup Physiol* 73: 98–104, 1996. doi:10.1007/BF00262816.
19. **Sandford GN**, **Laursen PB**, **Buchheit M.** Anaerobic speed/power reserve and sport performance: scientific basis, current applications and future directions. *Sports Med* 51: 2017–2028, 2021. doi:10.1007/s40279-021-01523-9.
20. **Berger NJ**, **Rittweger J**, **Kwiet A**, **Michaelis I**, **Williams AG**, **Tolfrey K**, **Jones AM.** Pulmonary O2 uptake on-kinetics in endurance-and sprint-trained master athletes. *Int J Sports Med* 27: 1005–1012, 2006. doi:10.1055/s-2006-923860.
21. **Fleg JL**, **Morrell CH**, **Bos AG**, **Brant LJ**, **Talbot LA**, **Wright JG**, **Lakatta EG.** Accelerated longitudinal decline of aerobic capacity in healthy older adults. *Circulation* 112: 674–682, 2005. doi:10.1161/CIRCULATIONAHA.105.545459.
22. **Van Hooren B**, **Plasqui G**, **Lepers R.** Physiological, spatiotemporal, anthropometric, training, and performance characteristics of a 75-year-old multiple world record holder middle-distance runner. *Int J Sports Physiol Perform* 18: 204–208, 2023. doi:10.1123/ijspp.2022-0284.
23. **Mikulic P**, **Bralic N.** Elite status maintained: a 12-year physiological and performance follow-up of two Olympic champion rowers. *J Sports Sci* 36: 660–665, 2018. doi:10.1080/02640414.2017.1329548.
24. **Pollock ML**, **Mengelkoch LJ**, **Graves JE**, **Lowenthal DT**, **Limacher MC**, **Foster C**, **Wilmore JH.** Twenty-year follow-up of aerobic power and body composition of older track athletes. *J Appl Physiol (1985)* 82: 1508–1516, 1997. doi:10.1152/jappl.1997.82.5.1508.
25. **Fox SM 3rd**, **Naughton JP**, **Haskell WL.** Physical activity and the prevention of coronary heart disease. *Ann Clin Res* 3: 404–432, 1971.
26. **Quanjer PH**, **Stanojevic S**, **Cole TJ**, **Baur X**, **Hall GL**, **Culver BH**, **Enright PL**, **Hankinson JL**, **Ip MS**, **Zheng J**; **Stocks J**; **ERS Global Lung Function Initiative.** Multi-ethnic reference values for spirometry for the 3–95-yr age range: the global lung function 2012 equations. *Eur Respiratory Soc* 40: 1324–1343, 2012. doi:10.1183/09031936.00080312.
27. **Johnson BD**, **Reddan WG**, **Pegelow DF**, **Seow KC**, **Dempsey JA.** Flow limitation and regulation of functional residual capacity during exercise in a physically active aging population. *Am Rev Respir Dis* 143: 960–967, 1991. doi:10.1164/ajrccm/143.5_Pt_1.960.
28. **Clauss M**, **Skattebo Ø**, **Dæhli MR**, **Valsdottir D**, **Bastani NE**, **Johansen EI**, **Kolnes KJ**, **Skålhegg BS**, **Jensen J.** Gross efficiency during rowing is not affected by stroke rate. *Med Sci Sports Exerc* 41: 1088–1095, 2023. doi:10.1249/MSS.0b013e3181912272.
29. **Phillips SM.** Dietary protein requirements and adaptive advantages in athletes. *Br J Nutr* 108, *Suppl 2*: S158–S167, 2012. doi:10.1017/S0007114512002516.
30. **Phillips S**, **Green H**, **Tarnopolsky M**, **Heigenhauser G**, **Grant S.** Progressive effect of endurance training on metabolic adaptations in working skeletal muscle. *Am J Physiol Endocrinol Physiol* 270: E265–E272, 1996. doi:10.1152/ajpendo.1996.270.2.E265.
31. **Louis J**, **Vercruyssen F**, **Dupuy O**, **Bernard T.** Nutrition for master athletes: is there a need for specific recommendations? *J Aging Phys Act* 28: 489–498, 2020. doi:10.1123/japa.2019-0190.
32. **American College of Sports Medicine.** *ACSM's Resource Manual for Guidelines for Exercise Testing and Prescription*. Philadelphia, PA: Lippincott Williams & Wilkins, 2012.
33. **de Jonee L**, **Bray GA.** The thermic effect of food and obesity: a critical review. *Obes Res* 5: 622–631, 1997. doi:10.1002/j.1550-8528.1997.tb00584.x.
34. **Tremblay MS**, **Aubert S**, **Barnes JD**, **Saunders TJ**, **Carson V**, **Latimer-Cheung AE**, **Chastin SF**, **Altenburg TM**, **Chinapaw MJ.** Sedentary behavior research network (SBRN)—terminology consensus project process and outcome. *Int J Behav Nutr Phys Act* 14: 75, 2017. doi:10.1186/s12966-017-0525-8.

Downloaded from journals.physiology.org/journal/jappl (084.088.141.041) on January 19, 2024.