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RESEARCH ARTICLE | *Case Studies in Physiology*

Case Studies in Physiology: Maximal oxygen consumption and performance in a centenarian cyclist

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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* 122: 430–434, 2017. First published December 29, 2016; doi:10.1152/japplphysiol.00569.2016.—The purpose of this study was to examine the physiological characteristics of an elite centenarian cyclist who, at 101 yr old, established the 1-h cycling record for individuals ≥100 yr old (24.25 km) and to determine the physiological factors associated with his performance improvement 2 yr later at 103 yr old (26.92 km; +11%). Before each record, he performed an incremental test on a cycling ergometer. For 2 yr, he trained 5,000 km/yr with a polarized training that involved cycling 80% of mileage at "light" rate of perceived exertion (RPE) ≤12 and 20% at "hard" RPE ≥15 at a cadence between 50 and 70 rpm. His body weight and lean body mass did not change, while his maximal oxygen consumption ($\dot{V}O_{2max}$) increased (31–35 ml·kg^{-1}·min^{-1}; +13%). Peak power output increased from 90 to 125 W (+39%), mainly because of increasing the maximal pedaling frequency (69–90 rpm; +30%). Maximal heart rate did not change (134–137 beats/min) in contrast to the maximal ventilation (57–70 l/min, +23%), increasing with both the respiratory frequency (38–41 cycles/min; +8%) and the tidal volume (1.5–1.7 liters; +13%). Respiratory exchange ratio increased (1.03–1.14) to the same extent as tolerance to $\dot{V}CO_2$. In conclusion, it is possible to increase performance and $\dot{V}O_{2max}$ with polarized training focusing on a high pedaling cadence even after turning 100 yr old.

NEW & NOTEWORTHY This study shows, for the first time, that maximal oxygen consumption (+13%) and performance (+11%) can still be increased between 101 and 103 yr old with 2 yr of training and that a centenarian is able, at 103 yr old, to cover 26.9 km/h in 1 h.

aging; centenarian; cycling; $\dot{V}O_{2max}$; pedaling cadence

THE NUMBER OF ELDERLY individuals (>65 yr old) will increase worldwide from 6.9% of the population in 2000 to a projected 19.3% in 2050, and persons older than 80 yr are the fastest growing segment of the population. Among this elderly population, there are more and more masters participating in competitive cycling and running. Participation and performance are increasing at a higher rate in the master groups than in other age groups (13, 17); however, there is still a lack of data on so-called "old-old master athletes." Among lifelong octogenarian athletes, new records in maximal oxygen consumption ($\dot{V}O_{2max}$) of 38 ml O$_2$·kg^{-1}·min^{-1} have been reported that are comparable with people who are sedentary and 40 yr younger (29). However, beyond the establishment of new performance records at an extremely old age, the possibility for improving their performance and $\dot{V}O_{2max}$ during this last period of life is a way to "add life to the life" rather than searching to "kill the death," whatever their sport histories (19).

MATERIALS AND METHODS

Subject. In February 2012, Robert Marchand (RM; born November 26, 1911) set a world record for 1-h track cycling in the over-100 age group at 24.250 km. He improved this record to 26.927 km in January 2014. He started cycling at the age of 15 and stopped at the age of 25, when he went to work as a gardener and wine dealer. He continued to work until 1987, when he retired at the age of 76.

RM volunteered to take part in the study. Before participation, he was informed of the risks and stresses associated with the protocol, and he gave his written voluntary informed consent for the tests and for the public reporting of his results. The present study conformed to the standards set by the Declaration of Helsinki, and the local research ethics committee (Comité Ethique et Aide à la Décision Médicale) approved all procedures (approval no. 201301). The subject was free of known cardiovascular, respiratory, and circulatory dysfunction. He was not taking prescribed medication. The subject underwent a classic cardiac examination, including an electrocardiogram. He performed specific maximal incremental tests 2 wk before the record attempt at the ages of 101 and 103 yr old, with regular electrocardiogram controls twice a year.

Experimental design and exercise protocols. For 2 yr, the subject trained 5,000 km/yr with a polarized training: 80% of mileage at "light" rate of perceived exertion (RPE) ≤12 and 20% at "hard" RPE ≥15. Training was not monitored with a heart rate (HR) monitor or for speed or power; however, the subject was aware of cycling below RPE 12 once a week, between 10 and 15 RPE once a week, and at RPE ≥15 every 2 wk. For each training session, he focused on a cadence range between 60 and 90 rpm on his gear. Two exercise tests were performed, one before and one after 2 yr of training.

All tests were at least 2 h postprandial, and the subject was asked to refrain from caffeine intake before testing on the test days. Before each track record, RM performed an incremental test on a cycling ergometer in the laboratory.

After familiarization with the laboratory and procedures, the subject performed the incremental protocol on an electronically braked cycle ergometer (Ergoline 900; Marquette Hellige, Bitz, Germany) to determine the maximal values of performance (power and speed),

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$\dot{V}O_{2max}$, the lowest power that elicited $\dot{V}O_{2max}$ ($p\dot{V}O_{2max}$), the power associated with RPE = 15 (hard), the maximal pedaling frequency, the cardiorespiratory parameters, and the oxygen cost of pedaling.

For the two exercise tests, he used the same double-link pedals (Proconcept) and cycling shoes (Adidas), as well as for the 1-h cycling best performance record.

After a warm-up of 15 min at 25 W, power output increased by 25 W every 3 min until the subject reached an RPE equal to 17 (very hard).

Data collection procedure. Before each test, body weight was measured with an electronic balance (799 Seca), and lean mass was quantified by skinfold measurements using a Harpenden skinfold caliper at three sites (triceps, suprailiac, and thigh). During the two tests, an electrocardiogram (Cosmed Quark b^2; Rome, Italy) was recorded beat by beat. Oxygen uptake, carbon dioxide production, expiratory minute ventilation, and respiratory frequency were recorded breath by breath throughout each test using a Cosmed Quark b^2, as previously reported (22), and maximal values were measured [$\dot{V}O_{2max}$, $\dot{V}CO_{2max}$, maximal expiratory minute ventilation ($\dot{V}E_{max}$), and maximal respiratory frequency (RF_{max}), respectively]. Before each test, the oxygen analysis system was calibrated according to the manufacturer's instructions, while the turbine flowmeter was calibrated using a 3-liter syringe (Quinton Instruments). Maximal value of respiratory exchange ratio (RER_{max}) was determined as the highest ratio of $\dot{V}CO_2$ to $\dot{V}O_2$. Oxygen blood saturation (Sa_{O_2}) was recorded every 2 min (Oxypleth; Novametrix Medical System, Walingford, CT) at the earlobe.

$\dot{V}O_{2max}$ attainment was confirmed by the following criteria (22): attaining a plateau in $\dot{V}O_2$ ($\Delta\dot{V}O_2 < 2.1\ ml \cdot kg^{-1} \cdot min^{-1}$), and this is the primary criterion of $\dot{V}O_{2max}$ attainment, and/or *1*) a RER greater than 1.05, *2*) a heart rate >90% of the theoretical maximal HR (16), and *3*) a subjective RPE >16 (3). To avoid an invasive examination, no blood sample was drawn for measuring the blood lactate concentration. The duration of the $\dot{V}O_{2max}$ plateau was calculated as the time sustained at a $\dot{V}O_2$ value >95% of $\dot{V}O_{2max}$, according to its experimental and biological $\dot{V}O_2$ variability (18).

During exercise, the subject was given strong verbal encouragement to exercise to volitional fatigue; however, the subject received no progress feedback. RPE (15) was recorded at the end of each stage for the incremental test.

One-hour cycling best performance record. The hour record is the record for the longest distance cycled in 1 h on a bicycle from a stationary start, according to Union Cyclist International (UCI) rules (article 3.5.026). Cyclists attempt this record alone on the track without other competitors present. It is considered perhaps the most prestigious record in all cycling and has been studied scientifically.

For his records, RM used two different bikes at an interval of 2 yr, and both bikes had the same characteristics according to the UCI rules, i.e., the same gear ratio and weight (7.15 kg). His gear ratio, using a tray of 49 teeth associated with a gear with 16 teeth, was ~6.54 m. The tires were gut Continental Tempo 22. Therefore, to beat his proper world record by 1 km/h (25.25 km/h, i.e., 420.8 m/min), RM had to cycle at an average cadence of 64–65 rpm.

Data analysis. Body surface area (BSA) was calculated according to the equation of Du Bois and Du Bois (6), where BSA = $0.20247 \times Height^{0.725} \times Weight^{0.425}$ with BSA in square meters, height in meters, and weight in kilograms.

Fat mass was calculated from the equation of Durnin and Womersley (7) for subjects ≥50 yr old.

Power output from the average speed of the 1-h world record was calculated from speed according to *Eq. 1* (5, 12):

$$\text{Power}(\text{W}) = 3.2V + 0.19V^3 \tag{1}$$

where *V* is the speed in meters per second.

The age-predicted maximal heart rate revisited was used for estimating the maximal heart rate according to *Eq. 2* (28):

$$\text{Maximal heart rate predicted}(\text{beats/min}) = 208 - 0.7 \times \text{Age} \tag{2}$$

where age is in years.

The oxygen pulse (O_2 pulse) was calculated according to *Eq. 3*:

$$O_2\ \text{pulse} = \dot{V}O_2/\text{HR} \tag{3}$$

where $\dot{V}O_2$ is in milliliters of O_2 per minute and heart rate (HR) is in beats per minute.

Since body dimensions directly influence stroke volume and O_2 pulse is related to the stroke volume response to exercise, adjustments for body dimensions or weight are included in studies aiming to evaluate the O_2 pulse response to exercise (21).

Therefore O_2 pulse corrected for body weight (hereinafter termed relative O_2 pulse) was calculated according to *Eq. 4*:

$$\dot{V}O_2/\text{HR rel} = O_2\ \text{pulse}/\text{weight} \tag{4}$$

where $\dot{V}O_2$/HR rel is in milliliters of $O_2 \cdot$per beat per kilogram, O_2 pulse is in milliliters per beat, and weight is in kilograms.

Maximal tidal volume (l/cycle) was also calculated as the ratio between $\dot{V}E$ and RF_{max}.

This equation in response to nonsteady-state incremental exercise testing demonstrates a linear pattern in a well-controlled data set of subjects referred for exercise testing (21).

The power reserve above $\dot{V}O_{2max}$ was calculated according to *Eq. 5*:

$$\text{Power reserve above } \dot{V}O_{2max}(\text{W}) = \text{Peak power output} - \text{Minimal powerat } \dot{V}O_{2max} \tag{5}$$

The slope of the regression line between $\dot{V}E$ (*y*-axis) and $\dot{V}CO_2$ (*x*-axis), which is considered to be the ventilatory response to CO_2, was calculated (4).

RESULTS

The subject's weight and lean body mass did not change between the two 1-h records (Table 1).

Table 1. *Anatomical and physiological variables before and after training*

	Before Training	After Training
Weight, kg	50.1	48.5
Height, m	1.52	1.52
Body mass index	21.7	21.0
Fat body mass, kg	13	11
Lean body mass, kg	43.6	43.2
Body surface, m^2	1.45	1.43
Field record power, W	80	103
Maximal oxygen uptake, ml O_2/min	1,553	1,698
Maximal carbon dioxide production, ml $CO_2 \cdot kg^{-1} \cdot min^{-1}$	31.9	37.1
Maximal respiratory exchange ratio	1.03	1.14
Maximal expiratory minute ventilation, l/min	57	70
Maximal respiratory frequency, cycles/min	38	41
Maximal tidal volume, l/cycle	1.5	1.7
Maximal oxygen pulse, ml O_2/beat	11.6	13.0
Maximal oxygen pulse, ml $O_2 \cdot kg^{-1} \cdot beat^{-1}$	0.23	0.27
Maximal oxygen cost of pedaling, ml $O_2 \cdot kg^{-1} \cdot W^{-1}$	19.4	17.0
Tolerance to CO_2 (slope of the regression line between $\dot{V}E$ and $\dot{V}CO_2$)	32.9	34.4
Specific power output, W/kg	1.8	2.5
Power output at $\dot{V}O_{2max}$, W	80	100
Power output at $\dot{V}O_{2max}$, W/kg	1.6	2.0
Power reserve above $\dot{V}O_{2max}$, W	10	25
Heart rate at rest, beats/min	65	63
Maximal heart rate at $\dot{V}O_{2max}$, beats/min	134	137

Performance and power. Between the two incremental tests, the peak power increased from 90 to 125 W (+39%), mainly because of the increase of maximal pedaling frequency (from 69 to 90 rpm; +30%; Fig. 1). The specific power output reached in the laboratory incremental test (peak specific power = 1.8–2.5 W/kg; +39%) and the power output at $\dot{V}O_{2max}$ (1.6–2.0 W/kg; +20%) increased to the same extent as those reached on the track during the establishment of the centenarian record (Table 1). Indeed, the field average record power calculated from the average speed during the track performance increased (80–103 W; +29%), which represents 89 and 82%, respectively, of the peak power output (Table 1). Therefore the increase of the metabolic scope allowed RM to beat his record with a lower fraction of his maximal peak power output. Indeed, the metabolic scope is the ratio of resting and the maximum metabolism rate for that particular species, as determined by oxygen consumption.

The oxygen cost of pedaling decreased by 19% (Table 1). RM increased his maximal pedaling frequency (from 69 to 90 rpm, +30%) after training and then attained a higher peak power output (Fig. 1). Furthermore, RM increased the power reserve above $\dot{V}O_{2max}$, given that the peak power exceeds $\dot{V}O_{2max}$ by more than two times after training (Table 1).

Cardiorespiratory variables. Between the two tests, $\dot{V}O_{2max}$ (31–35 ml·kg^{-1}·min^{-1}; +13%), $\dot{V}CO_{2max}$ (+16%), RER$_{max}$ (1.03–1.14; +11%), maximal ventilation (57–70 l/min; +23%), respiratory frequency (38–41 cycles/min; +8%), tidal volume (1.5–1.7 liters; +13%), tolerance to CO_2 evaluated by the slope of the regression line between $\dot{V}_E$ and $\dot{V}CO_2$ (32.9–34.4;+5%), and maximal O_2 pulse (0.23 vs. 0.27 ml O_2·kg^{-1}·beat^{-1}; +17%) increased (Table 1 and Fig. 1). In contrast, the maximal heart rate (134 vs. 137 beats/min) and the heart rate while sitting on the bicycle and at 0 W (65 vs. 63 beats/min) did not change.

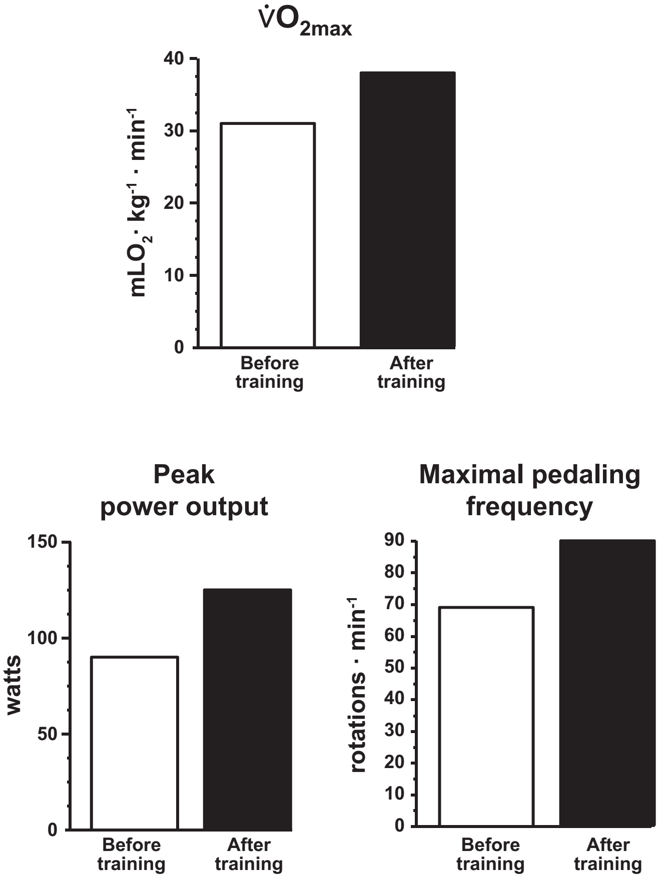

Fig. 1. Maximal oxygen uptake ($\dot{V}O_{2max}$), peak power output, and maximal pedaling frequency before and after training.

DISCUSSION

This study shows for the first time that at a very old age, $\dot{V}O_{2max}$ and performance could still be increased with training.

$\dot{V}O_{2max}$ and cardiorespiratory factors. $\dot{V}O_{2max}$ was not only high for a centenarian (31 ml·kg^{-1}·min^{-1}) but still increased slightly between the ages of 101 and 103 (Fig. 1). Given that lean body mass is a factor of influence for the decline in $\dot{V}O_{2max}$ with age in older subjects (1), RM has a lower fat mass than those reported for aging (11 vs. 20%), and his lean body mass did not change. Consequently, a part of the specific $\dot{V}O_{2max}$ was due to the fat mass decrease; however, considering that the absolute $\dot{V}O_{2max}$ also increased (+7%), an additional effect to that of muscle mass loss was observed on $\dot{V}O_{2max}$ (7% vs. 13%) and due to training. Therefore the increase in specific $\dot{V}O_{2max}$ was equally balanced between the fat mass loss and the increase in absolute $\dot{V}O_{2max}$.

This remarkable $\dot{V}O_{2max}$ in a centenarian is in the same range as the one considered necessary for being classified as fit in a group of men 42–61 yr old (20), above the reference values in a population 70–85 yr old [30.1 ± 4.8 (SD) ml·kg^{-1}·min^{-1}; 9], and more than the regression equation built into an epidemiologic study on elderly subjects until 90 yr old (14, 19). Indeed, his $\dot{V}O_{2max}$ was in the same range as that of a sedentary 50-yr-old man or those of an active 65-yr-old man and an endurance-trained 80-yr-old man (20, 28, 29). RM follows a qualitative training that prevents him from a $\dot{V}O_{2max}$ decrease that is known to be highly dependent upon the continuous magnitude of training stimulus, particularly in older male endurance athletes (23, 24).

In contrast to $\dot{V}O_{2max}$, the maximal heart rate (134 vs. 137 beats/min) and the heart rate while sitting on the bicycle and at 0 W (65 vs. 62 beats/min) did not change. Maximal heart rate was not higher than that predicted by *Eq. 2* (137 beats/min; 28); however, it was much higher than the one proposed by an epidemiologic study of elderly subjects (109 beats/min at the age of 101 yr old; 14). As in younger subjects, elite, very old athletes show cardiorespiratory values well above the predicted value, and polarized training maintains these values. As with $\dot{V}O_{2max}$, the O_2 pulse also changed in 2 yr (0.23 vs. 0.27 ml O_2·kg^{-1}·beat^{-1}, +17%). O_2 pulse, a readily available variable obtained during cardiopulmonary exercise testing, has been demonstrated to be a powerful predictor of mortality in patients with cardiovascular diseases (21), and it has been associated with the onset of exercise-induced ischemia (2). Indeed, RM has a higher value than the one reported in a 50-yr-old population (21). Fleg et al. (10) observed declines in $\dot{V}O_{2max}$ level and in oxygen pulse that accelerated with advanced decades. In addition, RM has a 20% lower body surface area (1.45 m^2) compared with the value reported in another study with the same O_2 pulse, as in 73-yr-old trained subjects, for instance (26).

RM had higher ventilation after training in terms of both an increase in tidal volume and respiratory frequency and in $\dot{V}CO_2$, in the sense of a possible strength increase that has been associated with ventilatory efficiency in older subjects (11). Given that in the first test the RER_{max} was rather low (1.03), one can challenge the $\dot{V}O_{2max}$ attainment. However, there are two reasons for trusting the maximal $\dot{V}O_2$ to be the real $\dot{V}O_{2max}$: *1*) a $\dot{V}O_2$ plateau was achieved despite the increased power output (16), and *2*) a lower RER value associated with $\dot{V}O_{2max}$ at exercise has been reported for elderly individuals (8). Therefore, based on the second test performed after training, this subject is capable of achieving a RER $>$1.10. The increase in ventilation during exercise has been reported to compensate for increased inefficiency of gas exchange, such that exercise remains essentially isocapnic. Therefore, in the elderly, the ventilatory response to hypercapnia is less than in young subjects, whereas ventilatory response to exercise is greater (4).

Peak power output and pedaling cadence increased after training. Peak specific power (+39%) and power at $\dot{V}O_{2max}$ (+25%) increased, mainly because of the cadence (69–90 rpm; +30%). Special focus must be given to the polarized training with a cadence range between 60 and 90 rpm, given that old (65.6 ± 2.8 yr) cyclists prefer a low cadence at $<$ 50 rpm that elicits less oxygen uptake per watt at 40 and 60% of their peak power output, with the aim of ensuring aerobic energy turnover (25). Stebbins et al. (27) reported that despite increased cadence being less efficient, subjects choose a higher cadence because it is less painful for the same power output. However, these data have been collected in young subjects, and RM is old and a highly unusual subject. This study's limitation is that RM is exceptional for being able to cycle at 27 km/h for 1 h; however, it is well known that performance gains in high-level athletes are more difficult to obtain.

It cannot be excluded that the enhanced performance with the hour record could have been achieved with regular training at a higher cadence. The use of two bikes at a 2-yr interval with two different tracks for each attempt could also impact the distance covered. Indeed, the first attempt was a 200-m track (International Cyclist Union, Aigle, Switzerland), and the second attempt was a 250-m track (Velodrome de Saint-Quentin-en-Yvelines). These factors likely impacted the track performance improvement; however, in standardized laboratory conditions, maximal power output, $\dot{V}O_{2max}$, and ventilatory factors have also been improved.

In conclusion, this study shows for the first time that it is still possible to improve performance after one's 100th birthday by using polarized training monitored with RPE and by focusing on a high pedaling cadence. This finding was determined because of the increase in $\dot{V}O_{2max}$ and maximal power. Consequently, 2 yr of new training is long enough for improving $\dot{V}O_{2max}$, even in an elderly subject. However, beyond this first centenarian case report, this performance and $\dot{V}O_{2max}$ improvement with polarized training must be examined in a larger population of the so-called "old-old" category of athletes that is now emerging.

DISCLOSURES

No conflicts of interest (financial or otherwise) are declared by the author(s).

AUTHOR CONTRIBUTIONS

V.L.B., G.D., L.M.-H., and J.-P.k. performed experiments; V.L.B., J.-P.k., and S.B. analyzed data; V.L.B., J.-P.k., and S.B. interpreted results of experiments; V.L.B., L.M.-H., L.L.M., I.M., T.L., J.-P.k., and S.B. edited and revised manuscript; V.L.B., T.L., and S.B. approved final version of manuscript; S.B. prepared figures; S.B. drafted manuscript.

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