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Case Studies in Physiology: Maximal Oxygen Consumption and Performance in a Centenarian Cyclist

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Running Head: $\dot{V}O_{2max}$ and performance increase after turning 100 years old

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ABSTRACT

The purpose of this study was to examine the physiological characteristics of an elite centenarian cyclist who, at 101 years old, established the one-hour cycling record for individuals ≥ 100 years old (24.25 km) and to determine the physiological factors associated with his performance improvement two years later at 103 years old (26.92 km; +11%). Before each record, he performed an incremental test on a cycling ergometer. For two years, he trained 5,000 km a year with a polarized training that involved cycling 80% of mileage at "light" RPE ≤ 12 and 20% at "hard" RPE ≥ 15 at a cadence between 50 and 70 rpm. Results: his bodyweight and lean body mass did not change, while his $\dot{V}O_{2max}$ increased (31 to 35 ml.kg^{-1}.min^{-1}; +13%). Peak power output increased from 90 to 125 W (+39 %), mainly due to increasing the maximal pedaling frequency (69 to 90 rpm; +30%). Maximal heart rate did not change (134 to 137 bpm) in contrast to the maximal ventilation (57 to 70 L.min^{-1}, +23%), increasing with both the respiratory frequency (38 to 41 cycle.min^{-1}; +8%) and the tidal volume (1.5 to 1.7 L; +13%). Respiratory Exchange Ratio increased (1.03 to 1.14) in 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 years old.

New & Noteworthy. This study shows, for the first time, that $\dot{V}O_{2max}$ (+13%) and performance (+11%) can still be increased between 101 and 103 years old with two years of training and that a centenarian is able, at 103 years old, to cover 26.9 km.h^{-1} in one hour.

Keywords: aging, centenarian, cycling, $\dot{V}O_{2max}$, pedaling cadence.

Introduction

The number of elderly individuals (> 65 years old) will increase worldwide from 6.9% of the population in 2000 to a projected 19.3% in 2050, and persons older than 80 years 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 $\dot{V}O_{2max}$ of 38 ml $O_2.kg^{-1}.min^{-1}$ have been reported that are comparable to people who are sedentary and 40 years younger (29). However, beyond the establishment of new performance records at an extremely old age, the possibility for improving their performance and maximal oxygen uptake ($\dot{V}O_{2max}$) during this last period of life is a way for "adding life to the life" rather than searching to "kill the death," whatever their sport histories (19).

Material and Methods

Subject

In February 2012, Robert Marchand (RM; born 26 November 1911) set a world record for one-hour 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 (CEADM) approved all procedures (approval number 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 two weeks before the record attempt at the ages of 101 and 103 years old, with regular electrocardiogram controls twice a year.

Experimental design and exercise protocols

For two years, the subject trained 5,000 km a year with a polarized training: 80% of mileage at “light” RPE ≤ 12 and 20% at “hard” RPE ≥ 15. Training was not monitored with an HR monitor, 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 two weeks. 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 two years of training.

All tests were at least two hours postprandial, and the subject was asked to refrain from caffeine intake prior to 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, Hellige, Markett, Bitz, Germany) to determine the maximal values of performance (power and speed), $\dot{V}O_{2max}$, the lowest power that elicited $\dot{V}O_{2max}$ ($p\dot{V}O_{2max}$), the power associated with the rate of perceived exertion (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 one-hour cycling best performance record.

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

Data collection procedure

Before each test, bodyweight was measured with an electronic balance (799 Seca), and lean mass was quantified by skinfolds measurements using a HARPENDEN skinfold caliper at three sites (triceps, suprailiac, 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 (Rome, Italy), as previously reported (22), and maximal values were measured ($\dot{V}O_{2max}$, $\dot{V}CO_{2max}$, $\dot{V}E_{max}$, and RF_{max}, respectively). Before each test, the oxygen analysis system was calibrated according to the manufacturer's instructions, while the turbine flow-meter was calibrated using a 3L syringe (Quinton instruments, USA). 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 (SaO_2) was recorded every two minutes (Oxypleth, Novametrix Medical System, Walingford, USA) at the earlobe.

$\dot{V}O_{2max}$ attainment was confirmed by the following criteria (22): attaining a plateau in $\dot{V}O_2$ ($\Delta\dot{V}O_2 < 2.1$ $ml.kg^{-1}.min^{-1}$), 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.

The one-hour cycling best performance record

The hour record is the record for the longest distance cycled in one hour 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 two years, 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 approximately 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 DuBois and DuBois (6), where BSA = 0.20247 x Height $^{0.725}$ x Weight$^{0.425}$ with BSA in m^2, height in m, and weight in kg.

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

Power output from the average speed of the one-hour world record was calculated from speed according to equation 1 (5, 12):

Power (W) = 3.2 V + 0.19 V^3 (equation 1)

where V is the speed in m.sec^{-1}.

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

Maximal heart rate predicted (beats per min [bpm]) = 208 – 0.7 × age (equation 2)

where age is in years.

The oxygen pulse (O_2 pulse) was calculated according to equation 3:

O_2 pulse = $\dot{V}O_2$ / HR (equation 3)

where $\dot{V}O_2$ is in mL O_2.min^{-1} and heart rate (HR) is in bpm.

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 (hereafter termed relative O_2 pulse) was calculated according to equation 4:

$\dot{V}O_2/HR$ rel = O_2 pulse/weight (equation 4)

where $\dot{V}O_2/HR$ rel is in mL $O_2 \times beat^{-1} \times kg^{-1}$, O_2 pulse in $mL.beat^{-1}$, and weight in kg.

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

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

The power reserve above $\dot{V}O_2max$ was calculated according to equation 5:

Power reserve above $\dot{V}O_2max$ (W) = Peak power output - minimal power at $\dot{V}O_2max$ (equation 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 one-hour records (Table 1).

Performance and power

Between the two incremental tests, the peak power increased from 90 to 125 W (+39%), mainly due to the increase of maximal pedaling frequency (from 69 to 90 rpm; +30%; Figure 1). The specific power output reached in the laboratory incremental test (peak specific power = 1.8 to 2.5 $W.kg^{-1}$; +39%) and the power output at $\dot{V}O_2max$ (1.6 to 2.0 W/kg; +20%) increased to the same extent as the one performed 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 to 103 W; +29%), which represents, respectively, 89% and 82% 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 (Figure 1). Furthermore, RM increased the power reserve above $\dot{V}O_2max$, given that the peak power exceeds $p\dot{V}O_{2max}$ by more than twice after training (Table 1).

Cardiorespiratory variables

Between the two tests : $\dot{V}O_{2max}$ (31 to 35 ml. kg^{-1}. min^{-1}; +13%), $\dot{V}CO_{2max}$ (+16%), RER_{max} (1.03 to 1.14; +11%), the maximal ventilation (57 to 70 L.min^{-1}; +23%), the respiratory frequency (38 to 41 cycle.min^{-1}; +8%), the tidal volume (1.5 to 1.7 L; +13%), the tolerance to CO_2 evaluated by the slope of the regression line between $\dot{V}E$ and $\dot{V}CO_2$ (32.9 to 34.4;+5%) and the maximal O_2 pulse (0.23 vs. 0.27 mL O_2.kg^{-1}.beat^{-1}; +17%) increased (Table 1 and Figure 1). In contrast, the maximal heart rate (134 vs. 137 bpm) and the heart rate while sitting on the bicycle and at 0 watts (65 vs. 63 bpm) did not change.

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 (Figure 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 years old (20), above the reference values in a population 70-85 years old (30.1 ± 4.8 $ml.kg^{-1}.min^{-1}$) (9), and more than the regression equation built into an epidemiologic study on elderly subjects until 90 years old (14, 19). Indeed, his $\dot{V}O_{2max}$ was in the same range as those of a sedentary 50-year-old man or those of an active 65-year-old man and an endurance trained 80-year-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 bpm) and the heart rate while sitting on the bicycle and at 0 watts (65 vs. 62 bpm) did not change. Maximal heart rate was not higher than those predicted by equation 2 (137 bpm) (28); however, it was much higher than the one proposed by an epidemiologic study of elderly subjects (109 bpm at the age of 101 years old) (14). As in younger subjects, elite, very old athletes show cardiorespiratory values well above the predicted value, and polarized training maintains it. As $\dot{V}O_{2max}$, the O_2 pulse also changed in two years (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-year-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 to the value reported in another study with the same O_2 pulse, as in 73-year-old trained subjects, for instance (26).

RM had higher ventilation after training in terms of both an increase in VT 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 greater than 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 due to the cadence (69 rpm to 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 years) cyclists prefer a low cadence at < 50 rpm that elicits less oxygen uptake per W 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, this data has 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 one hour; 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 two-year interval with two different tracks for each attempt could also impact the distance covered. Indeed, the first attempt was a 200m track (ICU Aigle, Switzerland), and the second attempt was a 250m 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 due to the increase in $\dot{V}O_{2max}$ and maximal power. Consequently, two years 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.

References

1. **Amara CE, Koval JJ, Johnson PJ, Paterson DH, Winter EM, and Cunningham DA**. Modelling the influence of fat-free mass and physical activity on the decline in maximal oxygen uptake with age in older humans. *Exp Physiol* 85: 877-886, 2000.

2. **Belardinelli R, Lacalaprice F, Carle F, Minnucci A, Cianci G, Perna G, and D'Eusanio G**. Exercise-induced myocardial ischaemia detected by cardiopulmonary exercise testing. *Eur Heart J* 24: 1304-1313, 2003.

3. **Bergh U, Ekblom B, and Astrand PO**. Maximal oxygen uptake "classical" versus "contemporary" viewpoints. *Med Sci Sports Exerc* 32: 85-88, 2000.

4. **Brischetto MJ, Millman RP, Peterson DD, Silage DA, and Pack AI**. Effect of aging on ventilatory response to exercise and CO2. *J Appl Physiol Respir Environ Exerc Physiol* 56: 1143-1150, 1984.

5. **di Prampero PE, Cortili G, Mognoni P, and Saibene F**. Equation of motion of a cyclist. *J Appl Physiol Respir Environ Exerc Physiol* 47: 201-206, 1979.

6. **Du Bois D, and Du Bois EF**. A formula to estimate the approximate surface area if height and weight be known. *Arch Intern Medicine* 17: 863–871, 1916.

7. **Durnin JV, and Womersley J**. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr* 32: 77-97, 1974.

8. **Edvardsen E, Hem E, and Anderssen SA**. End criteria for reaching maximal oxygen uptake must be strict and adjusted to sex and age: a cross-sectional study. *PLoS One* 9: e85276, 2014.

9. **Edvardsen E, Scient C, Hansen BH, Holme IM, Dyrstad SM, and Anderssen SA**. Reference values for cardiorespiratory response and fitness on the treadmill in a 20- to 85-year-old population. *Chest* 144: 241-248, 2013.

10. **Fleg JL, Morrell CH, Bos AG, Brant LJ, Talbot LA, Wright JG, and Lakatta EG**. Accelerated longitudinal decline of aerobic capacity in healthy older adults. *Circulation* 112: 674-682, 2005.

11. **Gonzales JU, Tucker SH, Kalasky MJ, and Proctor DN**. Leg strength is associated with ventilatory efficiency in older women. *Int J Sports Med* 33: 537-542, 2012.

12. **Gonzalez-Haro C, Galilea Ballarini PA, Soria M, Drobnic F, and Escanero JF**. Comparison of nine theoretical models for estimating the mechanical power output in cycling. *Br J Sports Med* 41: 506-509; discussion 509, 2007.

13. **Hawkins S, and Wiswell R**. Rate and mechanism of maximal oxygen consumption decline with aging: implications for exercise training. *Sports Med* 33: 877-888, 2003.

14. **Hollenberg M, Ngo LH, Turner D, and Tager IB**. Treadmill exercise testing in an epidemiologic study of elderly subjects. *J Gerontol A Biol Sci Med Sci* 53: B259-267, 1998.

15. **Howley ET**. .VO2max and the plateau--needed or not? *Med Sci Sports Exerc* 39: 101-102, 2007.

16. **Howley ET, Bassett DR, Jr., and Welch HG**. Criteria for maximal oxygen uptake: review and commentary. *Med Sci Sports Exerc* 27: 1292-1301, 1995.

17. **Jokl P, Sethi PM, and Cooper AJ**. Master's performance in the New York City Marathon 1983-1999. *Br J Sports Med* 38: 408-412, 2004.

18. **Katch VL, Sady SS, and Freedson P**. Biological variability in maximum aerobic power. *Med Sci Sports Exerc* 14: 21-25, 1982.

19. **Kusy K, and Zielinski J**. Aerobic capacity in speed-power athletes aged 20-90 years vs endurance runners and untrained participants. *Scand J Med Sci Sports* 24: 68-79, 2014.

20. **Laukkanen JA, Lakka TA, Rauramaa R, Kuhanen R, Venalainen JM, Salonen R, and Salonen JT**. Cardiovascular fitness as a predictor of mortality in men. *Arch Intern Med* 161: 825-831, 2001.

21. **Oliveira RB, Myers J, and Araujo CG**. Long-term stability of the oxygen pulse curve during maximal exercise. *Clinics (Sao Paulo)* 66: 203-209, 2011.

22. **Petot H, Meilland R, Le Moyec L, Mille-Hamard L, and Billat VL**. A new incremental test for VO(2)max accurate measurement by increasing VO(2)max plateau duration, allowing the investigation of its limiting factors. *Eur J Appl Physiol* 112: 2267-2276, 2012.

23. **Pimentel AE, Gentile CL, Tanaka H, Seals DR, and Gates PE**. Greater rate of decline in maximal aerobic capacity with age in endurance-trained than in sedentary men. *J Appl Physiol (1985)* 94: 2406-2413, 2003.

24. **Rogers MA, Hagberg JM, Martin WH, 3rd, Ehsani AA, and Holloszy JO**. Decline in VO2max with aging in master athletes and sedentary men. *J Appl Physiol (1985)* 68: 2195-2199, 1990.

25. **Sacchetti M, Lenti M, Di Palumbo AS, and De Vito G**. Different effect of cadence on cycling efficiency between young and older cyclists. *Med Sci Sports Exerc* 42: 2128-2133, 2010.

26. **Stathokostas L, Jacob-Johnson S, Petrella RJ, and Paterson DH**. Longitudinal changes in aerobic power in older men and women. *J Appl Physiol (1985)* 97: 781-789, 2004.

27. **Stebbins CL, Moore JL, and Casazza GA**. Effects of cadence on aerobic capacity following a prolonged, varied intensity cycling trial. *J Sports Sci Med* 13: 114-119, 2014.

28. **Tanaka H, Monahan KD, and Seals DR**. Age-predicted maximal heart rate revisited. *J Am Coll Cardiol* 37: 153-156, 2001.

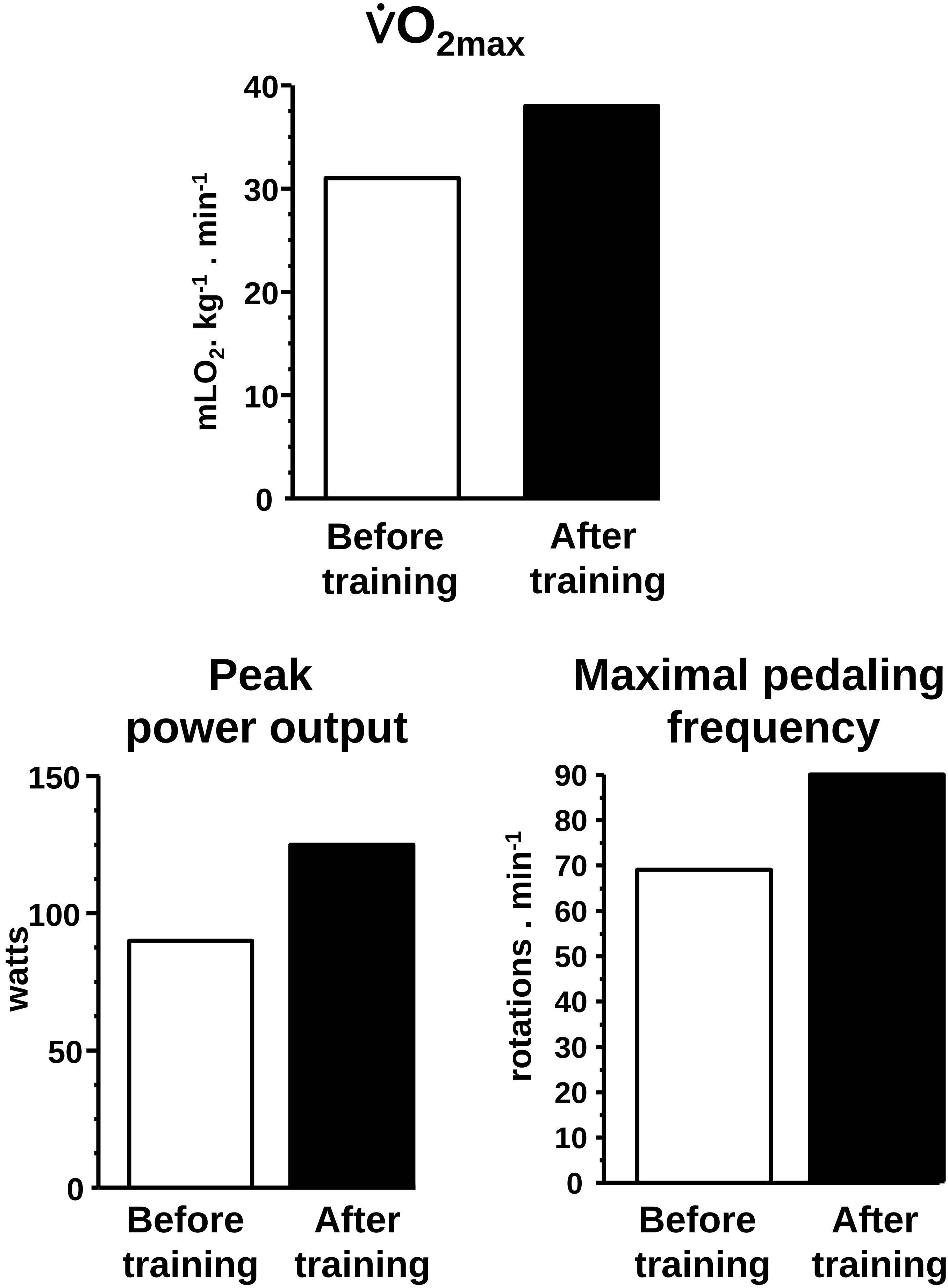
29. **Trappe S, Hayes E, Galpin A, Kaminsky L, Jemiolo B, Fink W, Trappe T, Jansson A, Gustafsson T, and Tesch P**. New records in aerobic power among octogenarian lifelong endurance athletes. *J Appl Physiol (1985)* 114: 3-10, 2013.

Figure Captions

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

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 ($mLO_2 . min^{-1}$)	1553	1698
Maximal carbon dioxide production ($mLCO_2 . Kg^{-1}. min^{-1}$)	31.9	37.1
Maximal respiratory exchange ratio	1.03	1.14
Maximal expiratory minute ventilation ($L . min^{-1}$)	57	70
Maximal respiratory frequency ($cycle . min^{-1}$)	38	41
Maximal tidal volume (L/cycle)	1.5	1.7
Maximal oxygen pulse ($mL\ O_2 . beat^{-1}$)	11.6	13.0
Maximal oxygen pulse ($mL\ O_2 . Kg^{-1} . beat^{-1}$)	0.23	0.27
Maximal oxygen cost of pedalling ($mL\ O_2 . Kg^{-1} . W^{-1}$)	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 ($W . Kg^{-1}$)	1.8	2.5
Power output at $\dot{V}O_{2max}$ (W)	80	100
Power output at $\dot{V}O_{2max}$ ($W . Kg^{-1}$)	1.6	2.0
Power reserve above $\dot{V}O_{2max}$ (W)	10	25
Heart Rate at rest ($beats . min^{-1}$)	65	63
Maximal heart rate at $\dot{V}O_{2max}$ ($beats . min^{-1}$)	134	137



V̇O2max
mLO2 . kg-1 . min-1
40
30
20
10
0
Before training
After training
Peak power output
watts
150
100
50
0
Before training
After training
Maximal pedaling frequency
rotations . min-1
90
80
70
60
50
40
30
20
10
0
Before training
After training