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1     **SIMILAR RELATIVE DECLINE IN AEROBIC AND ANAEROBIC POWER WITH AGE**  
2     **IN ENDURANCE AND POWER MASTER ATHLETES OF BOTH SEXES**

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14  
15  
16     **Running title:** Anaerobic and aerobic power in master athletes

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**26 ABSTRACT**

27 Lower physical activity levels in old age are thought to contribute to the age-related decline  
28 in peak aerobic and anaerobic power. Master athletes maintain high levels of physical activity  
29 with advancing age and endurance or power training may influence the extent to which these  
30 physical functions decline with advancing age. To investigate, 37-90-year-old power (n=20,  
31 45% female) and endurance (n=19, 58% female) master athletes were recruited. Maximal  
32 aerobic power was assessed when cycling two-legged ( $VO_2\text{Peak}_{2\text{-leg}}$ ) and cycling one-legged  
33 ( $VO_2\text{Peak}_{1\text{-leg}}$ ), while peak jumping (anaerobic) power was assessed by a countermovement  
34 jump. Men and women had a similar  $VO_2\text{Peak}_{2\text{-leg}}$  ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ,  $p=0.138$ ) and similar ratio of  
35  $VO_2\text{Peak}_{1\text{-leg}}$  to  $VO_2\text{Peak}_{2\text{-leg}}$  ( $p=0.959$ ) and similar ratio of peak aerobic to anaerobic power  
36 ( $p=0.261$ ). The  $VO_2\text{Peak}_{2\text{-leg}}$  ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) was 17% ( $p=0.022$ ) and the peak rate of fat  
37 oxidation (FATmax) during steady-state cycling was 45% higher in endurance than power  
38 athletes ( $p=0.001$ ). The anaerobic power was 33% higher in power than endurance athletes  
39 ( $p=0.022$ ). The  $VO_2\text{Peak}_{1\text{-leg}}:VO_2\text{Peak}_{2\text{-leg}}$  ratio did not differ significantly between disciplines,  
40 but the aerobic to anaerobic power ratio was 40% higher in endurance than power athletes  
41 ( $p=0.002$ ). Anaerobic power,  $VO_2\text{Peak}_{2\text{-leg}}$ ,  $VO_2\text{Peak}_{1\text{-leg}}$  and power at FATmax decreased by  
42 around 7-14% per decade in male and female power and endurance athletes.  
43 The cross-sectional data from 37-90-year-old master athletes in the present study indicates  
44 that peak anaerobic and aerobic power decline by around 7-14% per decade and this does  
45 not differ between athletic disciplines or sexes.

46  
47 **Key words:** master athletes, ageing, fatty acid oxidation,  $VO_2\text{Peak}$

48

## 49 Introduction

50 Ageing is accompanied by a progressive decline in bodily functions, ultimately resulting in  
51 death <sup>[1]</sup>. Such age-related decrements include a decrease in muscle mass, strength and power  
52 generating capacity <sup>[2]</sup>, and reductions in aerobic fitness <sup>[3]</sup>. Similar changes are also seen  
53 during disuse <sup>[4]</sup>. It is thus likely that the reduction in physical activity in old age <sup>[5]</sup> contributes  
54 significantly to the age-related reduction in muscle power and maximal oxygen uptake.

55  
56 Master athletes maintain high levels of physical activity into old age <sup>[6]</sup> and show impressive  
57 athletic feats <sup>[7]</sup> such as a 97-year-old man still cycling 5,000 km a year <sup>[8]</sup>. They have better  
58 physiological function <sup>[9]</sup>, longer lifespan, lower hospitalisation <sup>[10]</sup> and better quality of life in  
59 comparison to sedentary people of the same age <sup>[11]</sup>. Thus, regular exercise helps to combat  
60 the effects of ageing <sup>[12]</sup> and this provides an opportunity to distinguish the effects of ageing  
61 *per se* from the age-related reductions in physical activity <sup>[7]</sup>.

62  
63 Low cardiopulmonary fitness and neuromuscular function, and high body fatness are  
64 common features of ageing and risk factors for disability and all-cause mortality <sup>[13, 14]</sup>. These  
65 changes are not only due to low activity levels, since even in master athletes, performance  
66 levels, cardiopulmonary fitness and neuromuscular function decline <sup>[15-18]</sup>. However,  
67 endurance and power training impose different stresses upon cardiopulmonary and  
68 neuromuscular systems, with for instance higher ground reaction forces produced during  
69 higher running speeds such as **when** sprinting <sup>[19, 20]</sup>.

70  
71 It remains unknown whether the characteristics that determine power performance, such as  
72 very high peak muscle power, decline with ageing at different rates from those that determine  
73 endurance performance, such as high cardiopulmonary fitness and muscle aerobic potential.  
74 Given that endurance and power training promote divergent adaptations, such as increased  
75 skeletal muscle cross-sectional area and power in power athletes <sup>[21]</sup>, and increased  
76 cardiorespiratory fitness, oxidative and fat oxidation capacity in endurance athletes <sup>[22, 23]</sup>, we  
77 hypothesised that the anaerobic power is better preserved during ageing in power than  
78 endurance athletes, while the aerobic and fat oxidation capacity is better preserved in  
79 endurance athletes.

## 80 **Methods**

### 81 **Participants**

82 The study conformed to the latest revisions of the Declaration of Helsinki <sup>[24]</sup> and was  
83 approved by the Ärztekammer Nordrhein ethics committee, Düsseldorf, Germany (number  
84 2012157). Volunteers were recruited and assessed at the 18<sup>th</sup> European Veterans Athletics  
85 Championships (EVACs) at Weinau Stadium, Zittau, Germany between 16-25 August 2012.

86  
87 Volunteers provided written informed consent prior to participation. Those with a history of  
88 cardiovascular, neuromuscular or metabolic disease, or those who had a leg fracture in the  
89 past two years were excluded from the study. Participants were grouped into endurance and  
90 power disciplines by their primary entered events. Running events  $\geq 800$  m were classified as  
91 endurance, and  $\leq 400$  m and throwers were classified as power athletes (according to IAAF  
92 classifications: <https://www.iaaf.org/disciplines>). The age-graded performance for the main  
93 event of each athlete was calculated using the World Master Athletics age-grading calculator:  
94 <http://www.howardgrubb.co.uk/athletics/wmalookup06.html>. Participant characteristics  
95 are shown in Table 1.

### 96 **Experiments**

97 *Peak jumping (anaerobic) power:* Peak jumping power as a measure of peak anaerobic power  
98 <sup>[20]</sup> was assessed in 29 athletes on a Leonardo force platform (Novotec Medical, Pforzheim,  
99 Germany). The participants were instructed to perform a two-legged countermovement jump  
100 with the aim to raise the head and trunk as far as possible while freely moving their arms.  
101 Participants made two or three submaximal jumps to acquaint themselves with the  
102 procedure. They then performed three maximal efforts, each separated by 60 s rest and the  
103 attempt that gave the highest power (W) was recorded. The system computed the take-off  
104 velocity from the ground reaction force as described by Cavagna <sup>[25]</sup>. Instantaneous power  
105 was calculated as the product of force and velocity: Power (W) = Force (N) x Velocity ( $\text{m}\cdot\text{s}^{-1}$ ).  
106  
107 *VO<sub>2</sub>Peak<sub>2-leg</sub> (aerobic power):* VO<sub>2</sub>Peak<sub>2-leg</sub> was determined on a cycle ergometer (Jaeger  
108 Ergocycle) with a MetaLyzer 3B - R2 (Cortex BioPhysik GmbH, Leipzig, Germany) to measure  
109 VO<sub>2</sub> and VCO<sub>2</sub>. Participants started to cycle at a workload of 50 W and a cadence of 70 rpm.  
110

1  
2  
3 110 Workload was increased every 3 min with 50 W for men and 30 W for women until the  
4  
5 111 respiratory exchange ratio was higher than 1.0 for at least 1 min. From this point onwards,  
6  
7 112 workload was increased by 20 W every minute until the age-predicted HRmax (220 – age) was  
8  
9 113 exceeded, if the participant reached volitional exhaustion and/or the respiratory exchange  
10  
11 114 ratio was >1.1. Heart rate was measured using a Polar heart rate monitor (Polar Oy, Kempele,  
12  
13 115 Finland). The assessment was followed by a 5-min cool down at low cadence (~40 rpm) and  
14  
15 116 workload (25-75 W). The average of the values in the last 30 seconds of the last step was  
16  
17 117 taken as the  $VO_2\text{Peak}_{2\text{-leg}}$ . The maximal workload during the test was presented as maximal  
18  
19 118 aerobic power.

20 119

21 120 *FATmax (maximal fatty acid oxidation)*: The rate of fatty acid oxidation was estimated for  
22  
23 121 each workload as described previously [26]:

24  
25 122 
$$\text{Rate of Fatty Acid Oxidation (g}\cdot\text{min}^{-1}) = (1.695 \times VO_2) - (1.701 \times VCO_2)$$

26  
27 123 Where  $VO_2$  and  $VCO_2$  are given in  $L\cdot\text{min}^{-1}$  and negligible urinary nitrogen excretion is assumed.  
28  
29 124 *FATmax* was calculated by fitting the rate of fatty acid oxidation vs.  $\%VO_2\text{peak}_{2\text{-leg}}$  with a  
30  
31 125 polynomial, where the peak of the line was considered the maximal rate of fatty acid  
32  
33 126 oxidation.

34 127

35  
36 128  $VO_2\text{Peak}_{1\text{-leg}}$ : The  $VO_2\text{Peak}_{1\text{-leg}}$  during one-leg cycling was measured on a separate day from  
37  
38 129 all other assessments in a subgroup of 18 participants with the same equipment and  
39  
40 130 calibrations as the  $VO_2\text{Peak}_{2\text{-leg}}$  assessment. This assessment was included to estimate the  
41  
42 131 peak aerobic capacity of the active leg muscles. Where  $VO_2\text{Peak}_{2\text{-leg}}$  may be limited by the  
43  
44 132 cardio-respiratory supply of oxygen to the working muscles and/or by the uptake and  
45  
46 133 utilisation of available oxygen within muscle fibres<sup>[27, 28]</sup>, the cardio-respiratory supply of  
47  
48 134 oxygen to active leg muscles during one-legged cycling is not generally limiting. Therefore,  
49  
50 135 the  $VO_2\text{Peak}_{1\text{-leg}}$  more closely represents the leg muscle peak aerobic potential<sup>[29]</sup>.

51 136 For this assessment, the dominant leg was secured to the pedal on the cycle ergometer, while  
52  
53 137 the non-exercising leg was positioned on a central platform on the cycle ergometer to limit  
54  
55 138 extraneous movements. The participants were asked to minimise upper body movement  
56  
57 139 during the exercise. The workload began at 20 W at 70 rpm for the first two minutes of the  
58  
59 140 test, after which the workload was increased to 50 W for one minute and then by 10 W per  
60  
141 minute until volitional exhaustion or a cadence of 70 rpm could not be maintained. The

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3 142  $VO_2Peak_{1-leg}$  ( $L \cdot min^{-1}$ ) was taken as the highest value of 30 s rolling averages, which in all cases  
4  
5 143 occurred during the final minute of exercise.  
6

7 144

## 10 145 **Statistical analysis**

11 146 Data were analysed using SPSS (v.24 IBM). A two-factor ANOVA was used with sex and athletic  
12  
13 147 discipline (power vs. endurance) as between-factors. A discipline\*sex interaction indicates  
14  
15 148 that the effect of athletic discipline differs between men and women, determined by an  
16  
17 149 additional post hoc independent samples t-test. A stepwise linear regression was performed  
18  
19 150 with factors age, sex and discipline to assess the impact of these variables on the outcome  
20  
21 151 measures, with adjusted R-values presented. Age-related changes in ratios of jumping power  
22  
23 152 to  $VO_2Peak_{2-leg}$ , FATmax and the ratio of  $VO_2Peak_{1-leg} : VO_2Peak_{2-leg}$  were also analysed by this  
24  
25 153 method. Statistical significance was accepted at  $p < 0.05$ . Data are presented as mean ( $\pm SEM$ )  
26  
27 154 unless stated otherwise.  
28

29 155

## 31 156 **Results**

### 33 157 *Participant characteristics*

34  
35 158 Participant characteristics are shown in Table 1. There was no significant difference in the age  
36  
37 159 of the endurance and power athletes. Men were taller and had a larger body mass than  
38  
39 160 women ( $p < 0.001$ ). The body mass of the power athletes was larger than that of endurance  
40  
41 161 athletes ( $p = 0.001$ ). The BMI was higher in power than endurance athletes ( $p = 0.001$ ), but did  
42  
43 162 not differ significantly between men and women ( $p = 0.061$ ). The AGP did not differ  
44  
45 163 significantly between athletic discipline or between the sexes ( $p = 0.973$  and  $p = 0.718$ ,  
46  
47 164 respectively).  
48

49 165

### 50 166 *Jumping (anaerobic) power*

51 167 Men achieved a 64% higher jumping power than women (Table 2;  $p = 0.002$ ). However, when  
52  
53 168 normalised to body mass, there was no longer a difference between the sexes in peak jumping  
54  
55 169 power (Table 2;  $p = 0.070$ ). Power athletes achieved 58% higher power during vertical jumps  
56  
57 170 compared with long distance runners (Table 2;  $p = 0.003$ ) and 33% higher power than distance  
58  
59 171 runners when normalised to body mass (Table 2;  $p = 0.022$ ). The take-off velocity from the  
60

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3 172 jump was 19% higher in men than women (Table 2;  $p=0.004$ ), and was 15% higher in power  
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5 173 than endurance athletes (Table 2;  $p=0.027$ ).  
6

7 174

8  
9 175 *VO<sub>2</sub>Peak<sub>2-leg</sub>*

10  
11 176 Men displayed a 38% higher *VO<sub>2</sub>Peak<sub>2-leg</sub>* ( $L \cdot \text{min}^{-1}$ ) than women (Table 2;  $p=0.001$ ), but this  
12  
13 177 difference disappeared when normalised to body mass ( $\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ ) (Table 2;  $p=0.138$ ).  
14  
15 178 *VO<sub>2</sub>Peak<sub>2-leg</sub>* ( $L \cdot \text{min}^{-1}$ ) did not differ significantly between power and endurance athletes  
16  
17 179 (Table 2;  $p=0.592$ ), but when expressed per body mass it was 17% higher in endurance  
18  
19 180 athletes (Table 2;  $p=0.022$ ). Power (W) at *VO<sub>2</sub>Peak<sub>2-leg</sub>* was 37% higher in men than women  
20  
21 181 ( $p=0.024$ ), but did not differ between power and endurance athletes ( $p=0.817$ ).  
22

23 182

24 183 *FATmax*

25 184 There was a sex \* discipline interaction for *FATmax* ( $\text{g} \cdot \text{min}^{-1}$ :  $p=0.027$ ;  $\text{mg} \cdot \text{kg} \cdot \text{min}^{-1}$ :  $p=0.019$ )  
26  
27 185 which was reflected by a higher *FATmax* ( $\text{mg} \cdot \text{kg} \cdot \text{min}^{-1}$ ) in endurance than power athletes in  
28  
29 186 men ( $p<0.001$ ), but not in women ( $p=0.529$ ) and a similar *FATmax* ( $\text{mg} \cdot \text{kg} \cdot \text{min}^{-1}$ ) in male and  
30  
31 187 female endurance athletes ( $p=0.121$ ) and male and female power athletes ( $p=0.067$ ) (Table  
32  
33 188 2; Figure 1). There were no effects of sex ( $p=0.964$ ) or discipline ( $p=0.144$ ) on the percentage  
34  
35 189 of *VO<sub>2</sub>Peak<sub>2-leg</sub>* at which *FATmax* occurred.  
36

37 190

38 191 *VO<sub>2</sub>Peak<sub>1-leg</sub>* ( $L \cdot \text{min}^{-1}$ )

39  
40 192 *VO<sub>2</sub>Peak<sub>1-leg</sub>* was similar in men and women ( $p=0.159$ ), and in endurance and power athletes  
41  
42 193 ( $p=0.431$ ). During the single-leg cycling tests,  $\text{HR}_{\text{Peak}}$  reached  $86 \pm 1\%$  and  $81 \pm 1\%$  ( $p=0.433$ ) of  
43  
44 194 the values achieved during two-leg cycling for power and endurance athletes, respectively,  
45  
46 195 with no difference between sexes ( $p=0.252$ ). Power (W) at *VO<sub>2</sub>Peak<sub>1-leg</sub>* was not significantly  
47  
48 196 different between sexes or disciplines whether normalised to body mass or not ( $p>0.05$  in all  
49  
50 197 cases). The ratio of *VO<sub>2</sub>Peak<sub>1-leg</sub>* to *VO<sub>2</sub>Peak<sub>2-leg</sub>* did not differ significantly between disciplines  
51  
52 198 ( $p=0.404$ ) or sexes ( $p=0.959$ ).  
53

54 199



### 200 *Ratio of aerobic to anaerobic power*

201 There was no significant difference ( $p=0.261$ ) between men ( $7.1\pm 0.5\%$ ) and women  
202 ( $8.4\pm 0.6\%$ ) in the power at  $VO_2\text{Peak}_{2\text{-leg}}$  as a fraction of the jumping power. The same applied  
203 to the power at peak fat oxidation that was  $3.4\pm 0.4\%$  of power achieved during a vertical  
204 jump in both women and men ( $p=0.589$ ). The power (W) at  $VO_2\text{Peak}_{2\text{-leg}}$  as a fraction of that  
205 achieved during a vertical jump was higher ( $p=0.002$ ) in endurance ( $9.2\pm 0.6\%$ ) than power  
206 athletes ( $6.6\pm 0.4\%$ ). The power (W) at peak fat oxidation as a fraction of the jumping power  
207 was higher ( $p=0.007$ ) in endurance ( $4.1\pm 0.4\%$ ) than in power athletes ( $2.7\pm 0.3\%$ ).

### 209 *Age-related changes in aerobic and anaerobic power*

210 In table 3 it can be seen that age was the primary determinant of jumping power and  
211  $VO_2\text{Peak}_{2\text{-leg}}$ , both in absolute terms and when normalised to body mass. Sex was the second  
212 factor determining absolute jump power and  $VO_2\text{Peak}_{2\text{-leg}}$ , but discipline was more important  
213 than sex when jump power and  $VO_2\text{Peak}_{2\text{-leg}}$  were normalised to body mass (Table 3). For  
214 absolute FATmax there was a significant effect of age, but normalised to body mass the  
215 FATmax ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) was determined solely by athletic discipline (Table 3).

216  
217 The aerobic:anaerobic power ratio was not significantly affected by age or sex, but was higher  
218 in endurance than power athletes ( $p=0.001$ ; Table 2). However, the ratio of power at FATmax  
219 to that at  $VO_2\text{Peak}_{2\text{-leg}}$  was not affected by age, discipline or sex. The  $VO_2\text{Peak}_{1\text{-leg}}:VO_2\text{Peak}_{2\text{-leg}}$   
220 ratio was not significantly affected by age, sex or discipline.

221  
222 Absolute jumping power (W) (7.4% per decade,  $p<0.001$ ), relative jumping power (W/kg)  
223 ( $9.4\%$  per decade,  $p<0.001$ , Fig. 2A), absolute  $VO_2\text{Peak}_{2\text{-leg}}$  ( $\text{L}\cdot\text{min}^{-1}$ ) (11.2% per decade,  
224  $p<0.001$ ), relative  $VO_2\text{Peak}_{2\text{-leg}}$  ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) (9.0% per decade,  $p<0.01$ , Fig. 2B) and  
225  $VO_2\text{Peak}_{1\text{-leg}}$  ( $\text{L}\cdot\text{min}^{-1}$ ) (14.2% per decade,  $p<0.001$ ) declined with advancing age.

## 227 Discussion

228  
229 It is widely acknowledged that regular exercise is an effective way to combat or ameliorate  
230 the declines in physical function that occur with advancing age. Cross-sectional data from 37-  
231 90-year-old master athletes in the present study suggests that both peak anaerobic and

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3 232 aerobic power decline by around 7-14% per decade and that this trajectory did not differ  
4  
5 233 between power or endurance athletes. Even though master athletes perform better than age-  
6  
7 234 matched non-athletes <sup>[30]</sup>, the present results suggest age-related changes in the  
8  
9 235 neuromuscular and cardiopulmonary systems progress at similar rates, regardless of power  
10  
11 236 or endurance competitive specialisations.

12  
13 237 The master athletes in the present study were amongst the most athletic Europeans for their  
14  
15 238 age, as reflected by the cohort mean AGP of  $82.7 \pm 2.2\%$ . To put this into context, a 75-year-  
16  
17 239 old male marathon time of 80% AGP is 3h:46m:53s and the 100 m sprint time is 16:50s.  
18  
19 240 Despite these high achievements, physiological function clearly declined with increasing age.

20  
21 241

#### 22 242 *Power vs. endurance athletes*

23 243 The counter-movement jump is indicative of maximal anaerobic power <sup>[31]</sup>. In line with  
24  
25 244 previous observations <sup>[15, 20]</sup> we observed that the jumping (anaerobic) power per body mass  
26  
27 245 of power athletes was 33% higher than that of endurance runners, reflecting the expected  
28  
29 246 greater muscle power in power than endurance athletes. A novel contribution of our study is  
30  
31 247 that we also collected measurements of peak aerobic power for the same participants and  
32  
33 248 can compare across age and across disciplines. In healthy young adults,  $VO_{2Peak2-leg}$  during  
34  
35 249 whole body exercise is limited by the oxygen supply to the working muscles <sup>[32]</sup>. An indication  
36  
37 250 of the extent of the central limitation can be gained from the ratio of one- to two-leg cycling  
38  
39 251  $VO_{2Peak}$  <sup>[29]</sup>. The similar ratio in endurance and power athletes suggests that the  
40  
41 252 cardiovascular limitations to two-leg cycling are similar in both athletic groups, despite the  
42  
43 253 very different competitive specialisation of these athletes.

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45 254

46  
47 255 The  $VO_{2Peak1-leg}$  ( $L \cdot min^{-1}$ ) was similar for endurance and power athletes, despite the leg  
48  
49 256 muscle mass being larger for power athletes than for endurance runners <sup>[33]</sup>. This is most likely  
50  
51 257 due to the higher oxidative potential per unit muscle mass of endurance runners compared  
52  
53 258 with power athletes <sup>[34]</sup> to compensate for lower muscle mass. In addition to the higher  
54  
55 259 oxidative capacity per unit muscle mass of endurance athletes <sup>[34]</sup>, we found up to 45% higher  
56  
57 260 rate of fatty acid oxidation per unit body mass in endurance than power athletes at exercise  
58  
59 261 intensities of 30-70% of  $VO_{2Peak2-leg}$ . In line with this, previous studies have shown a  
60  
262 significant increase in muscle mitochondrial enzymes and those of fatty acid metabolism

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2  
3 263 following endurance training<sup>[35]</sup>. A higher rate of fat oxidation, as we observed for endurance  
4  
5 264 athletes, will make the muscle less dependent on glucose metabolism, sparing glycogen and  
6  
7 265 thereby increasing prolonged endurance performance<sup>[36]</sup>. Such an adaptation is not required  
8  
9 266 in power athletes who rely on anaerobic ATP generation from creatine phosphate and by  
10  
11 267 glycolysis for success in their discipline.

12 268

14 269 Interestingly, we found that the FATmax was higher in endurance than power athletes in men,  
15  
16 270 but not in women. Nevertheless, like in male ( $r=0.828$ ,  $p=0.011$ ) we also observed in female  
17  
18 271 ( $r=0.702$ ,  $p=0.016$ ) endurance athletes a correlation between body mass normalised FATmax  
19  
20 272 and maximal aerobic capacity. Whatever the cause of the absence of a higher FATmax in the  
21  
22 273 female endurance than power athletes, the FATmax appears to be related in both sexes and  
23  
24 274 disciplines with maximal aerobic capacity.

25 275

27 276 Based on previously published jump data in masters sprinters<sup>[15]</sup> and the  $VO_2\text{Peak}_{2\text{-leg}}$  data  
28  
29 277 from endurance runners<sup>[42]</sup>, it was estimated that the proportion of total power that can be  
30  
31 278 generated through aerobic processes is around 30% of the peak anaerobic power<sup>[17]</sup>. This  
32  
33 279 value is higher than the 9% and 7% we found in endurance and power athletes, respectively.  
34  
35 280 The discrepancy may be due to the previous study deriving maximal anaerobic power data  
36  
37 281 from master sprinters and the  $VO_2\text{Peak}_{2\text{-leg}}$  data from a different set of specifically-trained  
38  
39 282 master endurance runners, while we calculated this ratio directly from measurements  
40  
41 283 completed in the same individuals. The difference between 2-legged jumping and cycling is  
42  
43 284 also apparent, in that cycling is an alternating limb exercise where every time only one leg  
44  
45 285 produces power and little of the power is gained from musculo-tendinous elasticity,  
46  
47 286 compared to the 2-legged jump<sup>[43]</sup>. In any case, the aerobic power is only a small fraction of  
48  
49 287 the anaerobic power and this was true regardless of endurance or power training  
50  
51 288 specialisations. The fraction of anaerobic power that can be generated at the peak rate of  
52  
53 289 fatty acid oxidation is even smaller, at 4% for endurance and just 3% for power athletes.

54 290

### 55 291 *Ageing in power and endurance athletes*

57 292 We **expected** that the anaerobic power would be better preserved during ageing in power  
58  
59 293 than endurance athletes, while the  $VO_2\text{Peak}_{2\text{-leg}}$  would be better preserved in endurance

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3 294 athletes. This is important as throughout life both anaerobic power <sup>[2]</sup> and  $VO_2Peak_{2-leg}$   
4  
5 295 decrease with increasing age <sup>[3]</sup>. In this context it **was noted** that throughout the life span, the  
6  
7 296 anaerobic power is larger in power athletes <sup>[15]</sup> and aerobic power larger in endurance  
8  
9 297 athletes <sup>[16]</sup> than age-matched non-athletes. Similar to previous studies, we found that the  
10  
11 298 rate of decline in peak jump power <sup>[15, 20]</sup> was similar in power and endurance athletes. The  
12  
13 299 same applied to the decline in  $VO_2Peak_{2-leg}$ , which corresponds with other studies that  
14  
15 300 showed that the age-related rate of decline in  $VO_2Peak_{2-leg}$  was similar in endurance runners  
16  
17 301 and non-athletes <sup>[42, 44]</sup>, even though the absolute decline is faster in athletes <sup>[16]</sup>. This suggests  
18  
19 302 that there is an inherent ageing process that cannot be delayed.

20  
21 303 As a consequence of the similar rates of decline in anaerobic and aerobic power in both power  
22  
23 304 athletes and endurance runners, and men and women, the aerobic:anaerobic power ratio  
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25 305 remained constant with ageing and higher in endurance than power athletes. This  
26  
27 306 corresponds with the similar relative age-related decrements in running speed records of  
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29 307 endurance and power master athletes <sup>[17]</sup>. This consistent pattern of ageing appears to apply  
30  
31 308 to the performance in many other athletic disciplines, including swimmers <sup>[45]</sup>. The age-  
32  
33 309 related decrement is not limited to aerobic and anaerobic power, but also applies to the  
34  
35 310 maximal rate of fat oxidation. While older untrained adults have lower rates of fatty acid  
36  
37 311 oxidation than younger adults <sup>[37]</sup>, the ratio of workload at maximal rate of fatty acid oxidation  
38  
39 312 to workload at  $VO_2Peak_{2-leg}$  did not show an age-related decline in either discipline or sex in  
40  
41 313 our study. These proportional declines in work at maximal fatty acid oxidation, and maximal  
42  
43 314 aerobic and anaerobic power suggest that physiological systems determining these  
44  
45 315 parameters age proportionally, irrespective of athletic discipline, or even being an athlete at  
46  
47 316 all.

48  
49 317 Such a proportional age-related decline in physiological systems is also reflected by the stable  
50  
51 318 ratio of one-leg to two-leg performance across the ages, irrespective of discipline. This  
52  
53 319 indicates that in both endurance and power athletes the cardiovascular system remains the  
54  
55 320 main limitation of whole body  $VO_2Peak_{2-leg}$  during ageing and that the systems involved in  
56  
57 321 oxygen utilisation age proportionally <sup>[16]</sup>. Thus in older endurance and power athletes, the  
58  
59 322 oxygen delivering and consuming systems do not violate the principle of symmorphosis that  
60  
323 assumes that structures are matched to functional demands <sup>[46]</sup>.

### 324 *Study limitations*

325 In measurement of  $VO_{2peak2-leg}$ , athletes were stopped when they exceeded by more than  
326 10bpm the age-predicted maximal heart rate. It is possible that athletes did not achieve true  
327 maximal oxygen uptake in some cases even if their true maximal heart rate was greater than  
328 the methodological constraint that we applied for study governance. However, this bias  
329 applied to both sexes and to both power and endurance athletes equally. The present study  
330 was a cross-sectional design and recruitment targeted very high performing athletes, which  
331 constrained recruitment to relatively low overall sample sizes, although this is commonplace  
332 for studies of high performing athletes and the results provide new insights into a model of  
333 ageing which is at the peak of physiological performance [7]. While it is possible that the  
334 physiological profiles of the athletes are the product of heritable pre-disposition, the intensive  
335 exercise training programmes undoubtedly contributed to their outstanding physical  
336 capabilities. Furthermore, it is not possible to determine whether the divergent profiles of  
337 endurance and power athletes are due to their specific training programmes and/or to  
338 heritable factors.

### 339 *Perspective*

340 Master power athletes appear to exhibit a higher relative anaerobic power and lower relative  
341 aerobic power than master endurance athletes. However, the relative (%) annual decline in  
342 anaerobic power and aerobic power is similar in both athletic groups. The present data also  
343 suggests that during ageing there is a proportional decline in the power at the maximal rate  
344 of fat oxidation, irrespective of discipline and sex. It thus appears that there is an inherent,  
345 unavoidable (at least by exercise) ageing process that affects cardiopulmonary and  
346 neuromuscular systems important for exercise performance. Despite aerobic and anaerobic  
347 power declines with advancing age in masters athletes, the benefits of exercise during aging  
348 are evident as higher physical function than in age-matched non-athletes [30].

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3 485 **Figure Legends**  
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6 486 **Figure 1. Rates of fatty acid oxidation.** Measured during submaximal two-legged cycling and  
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8 487 expressed as a function of the %VO<sub>2</sub>Peak. Male power athletes (open circles) and endurance  
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10 488 runners (closed circles), and female power athletes (open squares) and endurance runners  
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12 (closed squares) and female. Sex\*Discipline interaction (p=0.019), reflected by a higher  
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15 490 FATmax in male (p<0.001), but not female (p=0.529), endurance than power athletes.  
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20 492 **Figure 2. Aerobic and anaerobic potential of masters athletes.** **A)** Absolute peak anaerobic  
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22 power (W·kg<sup>-1</sup>) decline from the age of 35 years, (r= -0.713, p<0.001). **B)** VO<sub>2</sub>Peak (mL·kg<sup>-1</sup>·min<sup>-1</sup>)  
23 493 decline from the age of 35 years, (r= -0.546, p<0.001). **C)** Power output at peak oxygen  
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25 494 uptake expressed as a percentage of the peak jump power (W) (r= 0.103, p=0.603). **D)** Power  
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27 (W) at FATmax as a percentage of the peak jump power (W) (r= -0.136, p=0.490). Male  
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29 endurance runners (closed circles), male power athletes (open circles), female endurance  
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31 runners (closed squares) and female power athletes (open squares).  
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**Table 1:** Characteristics of participants separated by discipline and sex.

Running Discipline	N	Age (years)	Height (m)	BM (kg)	BMI (kg·m <sup>-2</sup> )	AGP (%)
Endurance	8 ♂	62±5	1.74±0.04	66.1±3.6	21.8±1.1	86.3.0±5.5
	11 ♀	58±3	1.63±0.02*	54.9±1.4*	20.7±0.5	79.6±3.8
Power	11 ♂	58±5	1.79±0.03	78.6±2.9†	24.4±0.5†	78.1±4.9
	9 ♀	63±6	1.63±0.02*	61.4±2.7*†	23.0±0.6†	88.1±3.7

BM: body mass; BMI: body mass index; AGP: Age-graded performance. Data are shown as mean±SEM. \*indicates significant sex difference, †indicates significant difference between disciplines.

PROOF

**Table 2:** Muscle aerobic and anaerobic power of participants separated by discipline and sex

Running Discipline	Sex	JP (W)	JP/BM (W·Kg <sup>-1</sup> )	Velocity take-off (m·s <sup>-1</sup> )	VO <sub>2</sub> Peak <sub>2-leg</sub> (L·min <sup>-1</sup> )	VO <sub>2</sub> Peak <sub>2-leg</sub> /BM (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	Power VO <sub>2</sub> Peak <sub>2-leg</sub> (W)	HR (bpm)	VO <sub>2</sub> Peak <sub>2-leg</sub> (g·min <sup>-1</sup> )	FATmax (mg·kg <sup>-1</sup> ·min <sup>-1</sup> )	FATmax/BM (W)	Power Aer:Anaer Power (%)	VO <sub>2</sub> Peak <sub>1-leg</sub> (L·min <sup>-1</sup> )	Power VO <sub>2</sub> Peak <sub>1-leg</sub> (W)	VO <sub>2</sub> Peak <sub>1-leg</sub> : VO <sub>2</sub> Peak <sub>2-leg</sub>
Endurance	♂	3081±453 (n=6)	45.3±4.7	2.33±0.12	3.62±0.38	54.2±2.9	259±43	152±8	0.61±0.09	9.12±0.96	149±30	8.94±0.47	2.83±0.62 (n=4)	173±50	0.78±0.04
	♀	1985±179* (n=8)	35.5±2.5	2.10±0.11*	2.35±0.18*	42.9±3.4	188±16*	152±5	0.39±0.04	7.07±0.81	84±12*	9.34±0.92	1.95±0.27 (n=5)	108±12	0.84±0.04
Sprint	♂	4696±432 <sup>†</sup> (n=8)	56.9±3.8 <sup>†</sup>	2.75±0.11 <sup>†</sup>	3.17±0.26	40.0±2.7 <sup>†</sup>	258±28	157±5	0.38±0.03 <sup>†</sup>	4.75±0.30 <sup>†</sup>	126±14	5.98±0.42 <sup>†</sup>	2.25±0.26 (n=5)	123±30	0.79±0.04
	♀	2963±465* <sup>†</sup> (n=7)	47.9±7.7 <sup>†</sup>	2.23±0.12* <sup>†</sup>	2.54±0.16*	41.7±3.1 <sup>†</sup>	190±12*	164±5	0.38±0.04 <sup>▲</sup>	6.32±0.82 <sup>▲</sup>	81±13*	7.24±0.69 <sup>†</sup>	1.83±0.44 (n=4)	93±21	0.73±0.10

JP: Jumping power; JP/BM: Jumping power per body mass; VO<sub>2</sub>Peak<sub>2-leg</sub>/BM: two-leg VO<sub>2</sub>Peak per body mass; FATmax: maximal rate of fat oxidation; Aer:Anaer:

Aerobic:Anaerobic Power (%); VO<sub>2</sub>Peak<sub>1-leg</sub>: VO<sub>2</sub>Peak<sub>2-leg</sub>: VO<sub>2</sub>Peak of one- vs VO<sub>2</sub>Peak of two-leg cycling. Data are shown as mean±SEM. \*indicates significant sex difference,

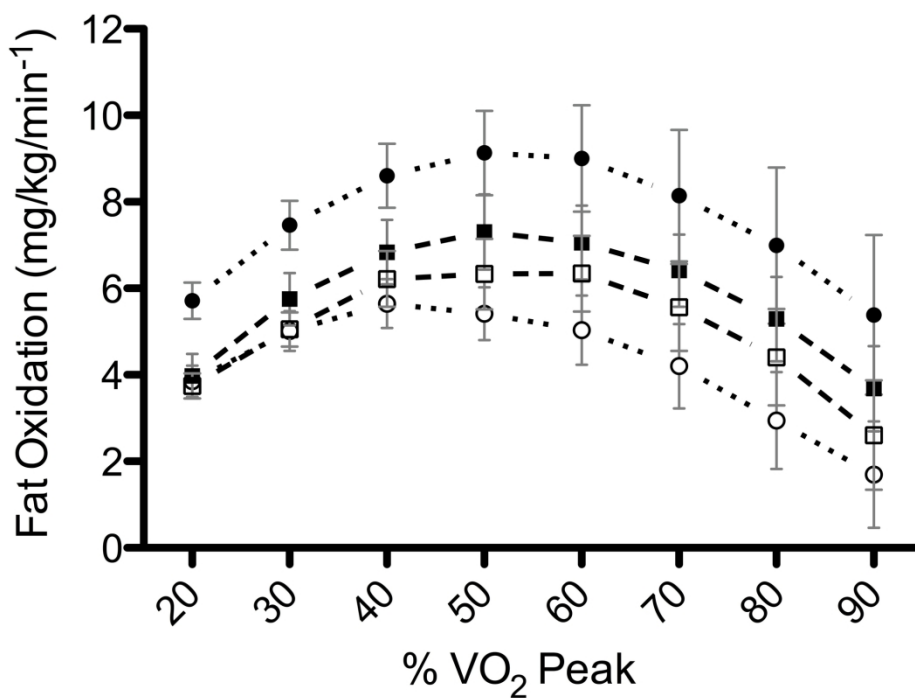
<sup>†</sup>indicates significant difference between disciplines, <sup>▲</sup>indicates interaction between sex and discipline.

**Table 3:** Stepwise linear regression between jumping power, aerobic capacity and rates of fatty acid oxidation with age, sex and discipline.

Jump Power (W)	Jump power per body mass (W·kg <sup>-1</sup> )	VO <sub>2</sub> Peak (L·min <sup>-1</sup> )	VO <sub>2</sub> Peak per body mass (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	FATmax (g·min <sup>-1</sup> )	FATmax per body mass (mg·kg <sup>-1</sup> ·min <sup>-1</sup> )
A: 0.391 <sup>***</sup>	A: 0.490 <sup>***</sup>	A: 0.374 <sup>***</sup>	A: 0.279 <sup>***</sup>	A: 0.132 <sup>*</sup>	D: 0.197 <sup>**</sup>
S: 0.652 <sup>***</sup>	D: 0.600 <sup>***</sup>	S: 0.637 <sup>***</sup>	D: 0.364 <sup>***</sup>		
D: 0.789 <sup>***</sup>	S: 0.680 <sup>***</sup>				

The R-values increase from top to bottom, representing the increased R when an additional factor is included; A: age; S: sex; D: Discipline; FATmax: maximal rate of fat oxidation; \*:  $P < 0.05$ . \*\*:  $P < 0.01$ ; \*\*\*:  $P < 0.001$ . Adjusted R-values are presented.

PROOF



98x76mm (600 x 600 DPI)

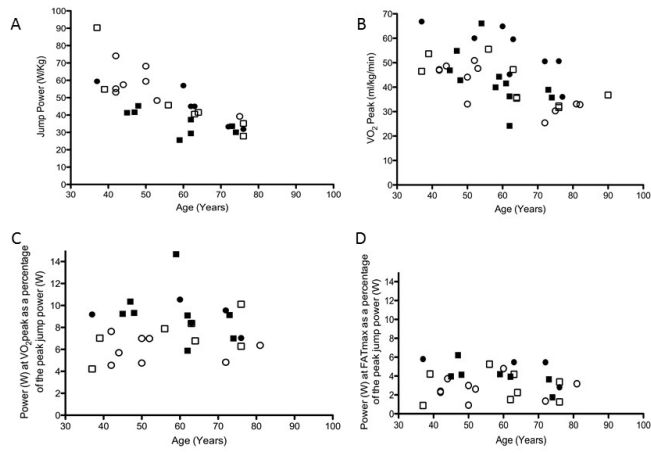


Figure 2

338x190mm (96 x 96 DPI)

## SIMILAR RELATIVE DECLINE IN AEROBIC AND ANAEROBIC POWER WITH AGE IN ENDURANCE AND SPRINT MASTER ATHLETES OF BOTH SEXES

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments to the Author

The authors have done very good work. The data is valuable because it is very difficult to have such master athletes as subjects. The results are clear and important for practice. All parts of the manuscript are of high scientific work.

The authors wish to thank the reviewer for their kind appraisal of the quality of our work and its place in the field of literature.

Reviewer: 2

Comments to the Author

This is an interesting manuscript which has studied the effects of age relate declines in in function in a cross-over - type design. It has done this by comparing explosive muscle function and aerobic capability in both sprint and endurance athletes. The paper provides some novel information about ageing that should be published.

The authors wish to thank the reviewer for their kind appraisal on the novelty of the work presented in our manuscript and their recommendation to publish. Thank you also for the suggestions listed below to improve the quality of the manuscript. All amendments made to the manuscript are highlighted in yellow and a line number given below.

Weakness / Suggestions for improvement

The number of subjects / master athletes is quite low.

The number of participants is lower than we would normally aim for when studying human physiology and ageing. This may limit the interpretation of the data. However, the participant group is highly specialised and belongs to the top performers of their age. This selection makes recruitment challenging indeed but at the same time we believe that this selection ensured a dataset that offers novel insights into the maximal achievable performance at a given age. Nevertheless, we have given the low number as a limitation in the study limitations section (lines 330-333).

The classification of 800m as a sprint even is dubious. What would happen if these were moved into the endurance category? Or a third category of middle distance athletes created?

1  
2  
3 If we created categories for power, middle and long distances, the group sizes would  
4 become 22, 9 and 8 respectively, and we believe these groups' sizes are too small.  
5 However, we do agree with the reviewer that 800 m is not classically defined as a  
6 power event and for this reason; we have re-classified  $\geq 800\text{m}$  as endurance and  
7  $\leq 400\text{m}$  as power (Lines 89-91). This has made very little difference to the overall  
8 results (with the exception of a newfound sex \* discipline interaction for FATmax  
9 measures; detail added to result section lines 184-188 and the discussion lines 269-  
10 274).

11  
12  
13 Further to this, we have also re-classified the athletes as "power" and "endurance".  
14 The reason for this is that athletes in our cohort competed over multiple events  
15 (heptathlon, pentathlon, throwing etc). The AGP presented is for the athletes "best  
16 performance" (ie, the highest AGP from all of the performances at this competition).  
17  
18

19 The rationale for the 1 legged protocol needs to be made much clearer earlier in the paper.

20  
21 The rationale for this protocol was detailed in the discussion. However, we have  
22 added further detail in the methods section (lines 130-135) as suggested.  
23  
24

25 It would be helpful if the details of each of the athletes (ages, events, physical  
26 characteristics etc) in a table (possibly as supplementary material?). This would be of utility  
27 to the reader.  
28

29  
30 We have discussed this amongst authors and decided that we cannot release the  
31 individual data as recommended. In the manuscript we have named the competition  
32 and the year. If we proceed to also release details of the specific event, ages and  
33 height etc., then it would theoretically be possible for somebody to look on the  
34 freely-available competitor listings and identify our study participants. This could be  
35 classed as a serious breach of participant confidentiality.  
36  
37

38 Measured maximum / peak heart rates should be included along with the caveat that there  
39 were imposed restrictions. How many reached VO<sub>2</sub> max without reaching the cut off for  
40 max HR?  
41  
42

43 We agree with this comment. The methodology has been fully described so that  
44 readers are aware of the methodological constraints affecting the data. 92% of  
45 athletes tested reached (or mostly greatly exceeded) predicted VO<sub>2</sub>max as  
46 determined in *Jones et al., Normal standards for an incremental progressive cycle*  
47 *ergometer test, 1985.*  
48

49 Further to this, one participant has been excluded from analysis (male, power  
50 athlete) due to premature termination of the 2-leg VO<sub>2</sub>peak test (49% Predicted  
51 VO<sub>2</sub>peak/65% max HR).  
52  
53

54 The Results section starting at line 24 does not seem to describe cover the main findings of  
55 Figure 1 in regard fat oxidation differences between two groups?  
56  
57

58 An additional line has been added to better explain the findings presented in figure  
59 1. This section now describes that finding that FATmax occurs at a similar %VO<sub>2</sub>peak  
60



1  
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3 between endurance and power athletes, however over the spectrum of exercise  
4 intensities, endurance athletes utilise significantly more fatty acid at given exercise  
5 intensities from 30-70% VO<sub>2</sub>peak. Lines 184-188  
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