



HAL
open science

The Physiological Characteristics of an 83-Year-Old Champion Female Master Runner

Thomas Cattagni, Vincent Grémeaux, Romuald Lepers

► **To cite this version:**

Thomas Cattagni, Vincent Grémeaux, Romuald Lepers. The Physiological Characteristics of an 83-Year-Old Champion Female Master Runner. *International Journal of Sports Physiology and Performance*, In press, 15 (3), pp.444-448. 10.1123/ijsp.2018-0879 . hal-02889378

HAL Id: hal-02889378

<https://u-bourgogne.hal.science/hal-02889378v1>

Submitted on 27 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

1 **The physiological characteristics of an 83-year-old champion female master**
2 **runner**

3

4 Thomas CATTAGNI ¹, Vincent GREMEAUX ^{2,3,4}, Romuald LEPERS ⁵

5

6 ¹ Inserm Unit 1179, Team 3: Technologies and Innovative Therapies Applied to Neuromuscular
7 diseases, UVSQ. CIC 805, Physiology-Functional Testing Ward, AP-HP, Raymond Poincaré
8 Teaching Hospital, Garches, France.

9 ² Swiss olympic medical center, Division de médecine physique et réadaptation, CHUV, 1011
10 Lausanne

11 ³ Institute of Sport Sciences, University of Lausanne, Lausanne, Switzerland.

12 ⁴ Pôle Rééducation-Réadaptation, CHU Dijon, France.

13 ⁵ INSERM UMR1093-CAPS, Université Bourgogne Franche-Comté, UFR des Sciences du
14 Sport, F-21000, Dijon

15

16 **Corresponding author:**

17 Thomas Cattagni

18 Hôpital Raymond Poincaré

19 104 bd Raymond Poincaré

20 92380, Garches

21 France

22 Email: thomas.cattagni@uvsq.fr

23 Tel: +33 1.47.10.79.00

24 **ABSTRACT**

25 **Purpose:** To examine the cardiorespiratory, muscular and skeletal characteristics of an 83-year-
26 old champion female master athlete (called DL in this study) who had set multiple world
27 running records in the 80-to-84-year-old age group. **Methods:** Measures of maximal oxygen
28 uptake (VO_{2max}), maximal heart rate (HR_{max}), maximal isometric torque for knee extensor
29 muscles, thigh and triceps surae muscle volumes, and bone mineral density (BMD) of the
30 proximal femur region were evaluated. Based on previously published equations, physiological
31 age was determined for VO_{2max} , HR_{max} and maximal isometric torque. Muscle volumes for the
32 dominant leg were compared with previously published sex- and age-matched data using Z-
33 scores. For BMD, T-score and Z-score were calculated. **Results:** DL had the highest VO_{2max}
34 ($42.3 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) ever observed for a female over 80 years of age, which gave her a
35 remarkable physiological age (27 years). In contrast, she had a physiological age closer to her
36 biological age for maximal isometric torque (90 years) and HR_{max} (74 years). The Z-scores for
37 thigh (0.4) and triceps surae (1.1) muscle volumes revealed that DL's leg muscles were affected
38 almost as much as her sex- and age-matched peers. The T-score (-1.7) for BMD showed that
39 DL had osteopenia but no osteoporosis, and the Z-score (0.7) showed that DL's BMD was
40 similar to that of females of the same age. **Conclusions:** This single case study shows that the
41 remarkable cardiorespiratory fitness coupled with intensive endurance training observed in a
42 female master athlete was not associated with specific preservation of her muscular and skeletal
43 characteristics.

44

45 **KEYWORDS**

46 Cardiorespiratory fitness; Neuromuscular function; Maximal oxygen uptake; Bone mineral
47 density; MRI.

48

49 **INTRODUCTION**

50 Master athletes, being free from the negative influence of physical inactivity, are considered as
51 models for primary biological aging.¹ Study of the physiological characteristics of high-
52 performance master athletes is essential to improve knowledge about the limits of human
53 physiology with age.

54 With performance in athletic endurance events being mainly related to aerobic capacity, master
55 athletes generally present with well-preserved aerobic capacity, as revealed by their high levels
56 of maximal oxygen uptake (VO_{2max}). VO_{2max} values of approximately $40\text{-}45 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$
57 (comparable with that observed in sedentary young healthy males) have been reported in 65-
58 to-80-year-old champion male athletes,^{2,3} while only $\sim 20\text{-}25 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ is generally
59 observed in age-matched untrained people.⁴ Two studies even reported a VO_{2max} of $50 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$
60 for an 80-year-old male,⁵ and a master runner with multiple world records.⁶ Female
61 master athletes aged between 60 and 70 years presented a VO_{2max} of approximately $38 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$.⁷
62 Like males, their VO_{2max} is comparable to their younger sedentary counterparts
63 [VO_{2max} : $\sim 30\text{-}35 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$]⁴ and considerably higher than their less physically active age-
64 matched peers [VO_{2max} : $\sim 16\text{-}21 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$].⁴ To date, the VO_{2max} of female master athletes
65 aged over 70-80 years is poorly documented and the VO_{2max} of the most elite remains to be
66 investigated to estimate the maximum limit of aerobic capacity in older females.

67 While aerobic capacity is known to be related to cardiovascular health, it is also related to
68 skeletal muscle health.⁸ However, a recent meta-analysis revealed that age-related declines in
69 muscular strength were not prevented in male master athletes competing in endurance events.⁹
70 In addition, while males and females may undergo somewhat divergent deterioration of skeletal
71 muscle function with advancing age, perhaps due to reductions in sex-specific hormones, most
72 conclusions regarding the skeletal muscle function of master athletes have been based on data

73 collected in males only.^{9,10} The skeletal muscle characteristics of older female master athletes
74 thus remain to be investigated.

75 While the benefits of chronic endurance exercise have been observed in cardiovascular and
76 muscle function, the benefit for skeletal function is not clear. Wiswell et al.¹¹ showed that
77 bone mineral density can be maintained by running in older active males. In contrast, no
78 specific protection of bone mineral density (BMD) was observed in post-menopausal female
79 master runners.¹² However, it is not known whether this lack of bone protection is also observed
80 in female master runners with very high fitness levels.

81 This case study aimed to present and compare some physiological characteristics of a champion
82 female master runner (called DL in this study) with those of females of the same age.

83

84 **MATERIALS AND METHOD**

85 **Subject**

86 At the time of the evaluation (June 2017), DL was 83 years old. She was a French Caucasian
87 retired beautician, living in Burgundy, France. Her anthropometric characteristics are displayed
88 in Table 1. DL had broken three world records (3,000, 5,000 and 10,000 m running) in the 80-
89 to-84-year-old age-group category, by the age of 80. For example, her record in 10,000 m
90 outdoor running was 0:55:26. She was still taking part in both walking and running
91 competitions at the time of evaluation. DL volunteered and was informed about the nature and
92 aims of the study, as well as the associated risks and discomfort prior to giving her written
93 consent to participate in the investigation. The protocol was in conformity with the Declaration
94 of Helsinki (last modified in 2013).

95

96 Typical training and competition schedule (S.1), sport history (S.2), medical history (S.3), and
97 athletics performances/records (Supplemental Table 1) of DL are available as an online
98 supplement.

99

100 **Experimental procedure, measurements & data analysis**

101 The following assessments are displayed in the order in which the tests were performed.

102

103 *Maximal voluntary contraction torque of the knee extensor muscles*

104 Torque measurements on the right (dominant) leg were performed on an isokinetic
105 dynamometer (System pro 4, Biodex Medical System, New York). The subject was seated on
106 the dynamometer chair with a 90° hip angle. The knee joint axis was aligned with the
107 dynamometer axis. The lever arm was attached 2 cm above the medial malleolus with a non-
108 compliant strap. The maximal voluntary contraction (MVC) peak torque of the knee extensors
109 was measured during isometric (MVC_{ISO}) and concentric contractions. After a warm-up, DL
110 performed two consecutive 5-s MVC_{ISO}, separated by a 1-min rest period, with the right leg
111 positioned at 70° of flexion (0°=fully extended). After a 1-min rest period, DL successively
112 performed 2 concentric MVCs at 60°·s⁻¹ (MVC₆₀) with a 95° range of motion (from 5° to 100°
113 of knee flexion). A 1-min rest period was respected between trials. For each type of contraction
114 (e.g. MVC_{iso}), the peak torque of both trials was retained for analysis.

115

116 *Heart rate and gas exchange during maximal treadmill test*

117 Because the subject was not familiar with treadmill running, a variable speed/grade procedure
118 was used. The test consisted of running at 7 km·h⁻¹ (0% slope) for 3 min, 8 km·h⁻¹ (0% slope)
119 for 3 min, and 9 km·h⁻¹ (0% slope) for 3 min. After the 9th min, speed was maintained at 9 km/h
120 but the slope was increased by 1% every minute until volitional exhaustion. The subject stopped
121 the test at the end of the 3% stage after 12 min of effort. Heart rate and respiratory gas exchange
122 parameters were recorded continuously during the test and maximal values were determined.

123 During the incremental treadmill test, heart rate was recorded every second using a heart rate
124 monitor (Polar RS300; Polar Electro Oy, Kempele, Finland), and maximal heart rate (HR_{max})
125 was defined as the highest value recorded during the last 30 s of the test. Gas exchange during
126 the test was collected using a breath-by-breath portable gas analyzer (Cosmed K4b², Rome,
127 Italy). VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$) and maximal carbon dioxide production (VCO_{2max} , $ml \cdot kg^{-1} \cdot min^{-1}$)
128 were both defined as the maximal value recorded over a 30-s period during the test. Maximal
129 value of respiratory exchange ratio was determined as the highest ratio between the volumes of
130 oxygen uptake and carbon dioxide production. Since O_2 pulse during cardiopulmonary exercise
131 testing has been associated with the onset of exercise-induced ischemia¹³, and is a powerful
132 predictor of mortality in patients with cardiovascular disease,¹⁴ it was also calculated.

133

134 *Lower Limb MRI*

135 Bilateral magnetic resonance imaging (MRI) scans of both lower limbs were performed using
136 a 3.0 Tesla MRI scanner (Siemens Trio, Berlin, Germany) with the participant in supine lying,
137 with knees and hips fully extended. Scanning parameters included: repetition time=723 ms;
138 echo time=10 ms; $\alpha=140^\circ$; field of view=400x400 mm; pixel size=0.714 mm; width=560
139 pixels; Height=448 pixels; slice thickness=5 mm; slice increment 5 mm; number of slices=162.
140 Data were transferred in DICOM format.

141 For both legs, the triceps surae, tibialis anterior, quadriceps and other thigh muscles (OTM,
142 including knee flexor and adductor muscles, and sartorius) were manually outlined for all the
143 slices of the MRI images using 3D image analysis software (Mimics, Materialise, Belgium).
144 Examples of muscle area determination are presented in Fig.1A for the thigh muscles, and in
145 Fig.1B for the calf muscles. The volume of each muscle or muscle group was calculated from
146 3D reconstruction (selected option on the mimic software: Optimal). A view of the 3D
147 reconstruction is presented in Fig.1C.

148

149 *Bone mineral density (BMD)*

150 BMD was assessed from dual energy X-ray absorptiometry scan (DXA) (Hologic Bone
151 Densitometer system n°83752A, model Discovery A, Hologic Company, Marlborough, MA
152 01752, United States) for the left proximal femur region including the femoral neck,
153 intertrochanteric region, greater trochanter.

154

155 **Statistical analysis**

156 While chronological age is determined by date of birth, physiological age can vary according
157 to numerous health metrics. In this study, we chose to compare some physiological
158 characteristics (HR_{max} , VO_{2max} , MVC_{ISO} , and MVC_{60}) of DL by providing her estimated
159 physiological age based on equations previously established in large samples. For HR_{max} , we
160 used the equation (1) of Tanaka et al.¹⁵, obtained from a meta-analysis including 351 studies
161 and 18,712 individuals. For VO_{2max} , we used the equation (2) of Myers et al.¹⁶, obtained from
162 a database including the VO_{2max} (recorded during a maximal treadmill test) of 3,158 healthy
163 females aged 20-79 years. For MVC_{ISO} , we used the equation (3) of Harbo et al.¹⁷, obtained
164 from a database including the MVC_{ISO} of 85 females aged 21–75 years. For MVC_{60} , we used
165 the equation (4) of Neder et al.¹⁸, obtained from a database including the MVC_{60} of 51 females
166 aged 20–80 years.

167

$$(1) \text{ Physiological age based on } HR_{max} = (208 - HR_{max}) / 0.7$$

$$(2) \text{ Physiological age based on } VO_{2max} = - (VO_{2max} + 0.127 \times weight_{(ibs)} - 66.2) / 0.39$$

$$(3) \text{ Physiological age based on } MVC_{ISO} = - (MVC_{ISO} - 216 \times height_{(m)} - 0.88 \times weight_{(kg)} + 201) / 0.96$$

$$(4) \text{ Physiological age based on } MVC_{60} = - (MVC_{60} - 1.63 \times weight_{(kg)} - height_{(m)} + 41.8) / 1.36$$

171

172

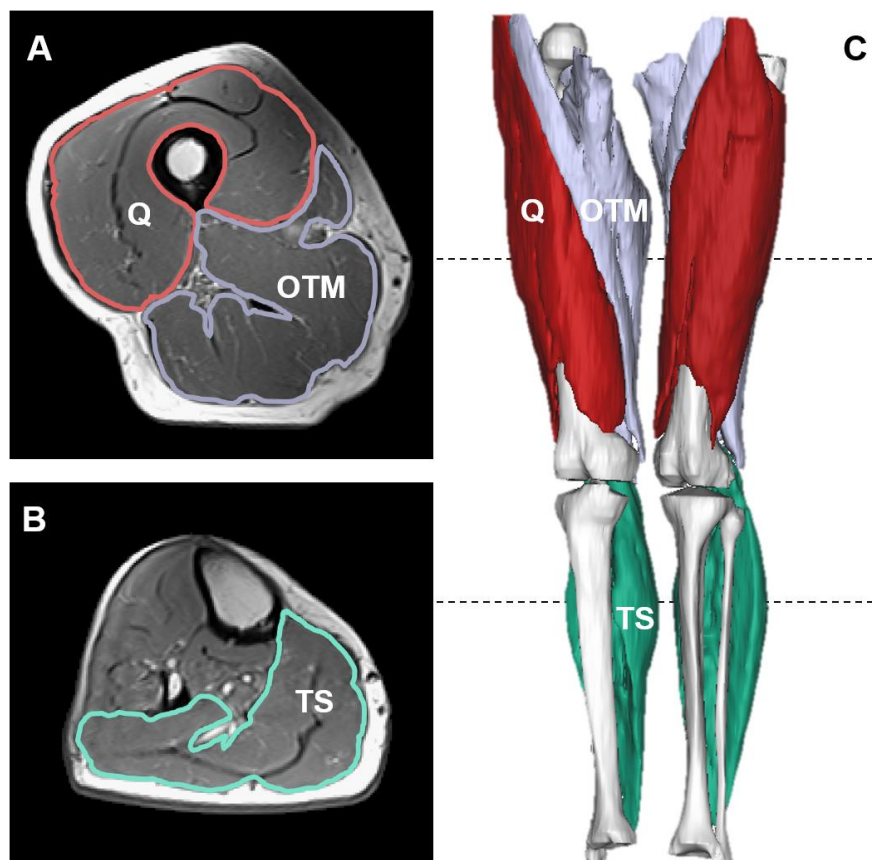
173 For the total thigh, quadriceps and other thigh muscle volumes, data was normalized using Z-
174 scores with individual data expressed as the number of standard deviations from the mean of
175 the ‘healthy older females’ group in the study by Maden-Wilkinson et al.,¹⁹ calculated as:

$$Z\text{-score} = (\chi - \mu) / \sigma$$

176
177
178 where χ is the value for DL, and μ and σ are the mean and standard deviation respectively, of
179 the older female sample. While reports of triceps surae muscle volume in older females are rare,
180 Z-scores were obtained from the study by Csapo et al.,²⁰ which measured triceps surae volume
181 in five healthy Japanese females aged ~83 years.

182
183 To determine whether DL had a risk of bone fracture despite her high physical activity level,
184 T-scores of BMD were used to compare DL with healthy young females with peak bone mass
185 according to the manufacturer's instructions and the World Health Organization.²¹ A T-score
186 between +1 and -1 denotes normal bone density. A T-score between -1 and -2.5 indicates low
187 bone density or osteopenia. A T-score of -2.5 or lower reveals the presence of osteoporosis. Z-
188 scores for BMD, providing a comparison with the bone density of people of the same age and
189 sex as the patient, were also obtained. A negative Z-score of -2.5 or less should raise concern
190 about a secondary cause of osteoporosis.

191



192
193

194 **Figure 1: Muscle segmentation of right (dominant) leg and volume reconstruction of**
195 **muscles and bones of both legs of the subject.**

196 A presents a magnetic resonance image at the mid-point of the femur of the right leg. B presents
197 a magnetic resonance image in the first third of the tibia of the right leg. C represents the 3D
198 reconstruction of muscle and bone volumes of both legs. Q: quadriceps; OTM: other thigh
199 muscles; TS: triceps surae.

200 **RESULTS**

201 As displayed in Table 1, DL had an exceptional $\text{VO}_{2\text{max}}$ ($42.3 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and normal muscle
202 strength for her age. Her lower limb muscle volumes were just slightly better than expected for
203 her age (Table 2). The bone mineral density was $0.739 \text{ g}\cdot\text{cm}^{-2}$ (T-score: -0.8; Z-score: 1.5) for
204 the femoral neck, $0.523 \text{ g}\cdot\text{cm}^{-2}$ (T-score: -1.9; Z-score: -0.3) for the greater trochanter, 0.986
205 $\text{g}\cdot\text{cm}^{-2}$ (T-score: -0.8; Z-score: 1.6) for the intertrochanteric region and $0.745 \text{ g}\cdot\text{cm}^{-2}$ (T-score:
206 -1.7; Z-score: 0.7) for the total of the left proximal femur region.

207
208 **DISCUSSION**

209 This single case study reported, for the first time, some physiological characteristics of a high-
210 level female master runner aged over 80 years.

211 During the maximal treadmill test, DL had a respiratory exchange ratio at $\text{VO}_{2\text{max}}$ just below 1,
212 indicating a possible underestimation of her true $\text{VO}_{2\text{max}}$. Despite this, DL presented, to the best
213 of our knowledge, the highest value of $\text{VO}_{2\text{max}}$ ever observed for an octogenarian female. On
214 the basis of her $\text{VO}_{2\text{max}}$, we showed that she had a physiological age of ~ 27 years. Her $\text{VO}_{2\text{max}}$
215 was slightly higher than in young females ($\sim 30\text{-}35 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)⁴ and 60-to-69-year-old
216 endurance-trained females ($\sim 38.0 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$),⁷ but considerably above the mean values in
217 females aged 70-to-79-year-old ($\sim 16\text{-}21 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$).⁴ While DL had a low body mass
218 compared to the populations of young and elderly females, her absolute $\text{VO}_{2\text{max}}$ ($1.99 \text{ l}\cdot\text{min}^{-1}$)
219 was twice that of females aged 70-to-79-year-old ($\text{VO}_{2\text{max}}$: $1.05 \text{ l}\cdot\text{min}^{-1}$) and comparable to that
220 of young females (20-25 years, $\text{VO}_{2\text{max}}$: $2.04 \text{ l}\cdot\text{min}^{-1}$).⁴ It can be assumed that DL had some
221 hereditary advantages for cardiorespiratory fitness, $\text{VO}_{2\text{max}}$ and its trainability being related to
222 genetic predisposition.²² However, age-related decline in $\text{VO}_{2\text{max}}$ could have been prevented,
223 due to her participation in a training program for competitive running performance of distances
224 up to 10km, from the age of 69 years. Indeed, it is well known that older persons can minimize
225 the reduction in age-related $\text{VO}_{2\text{max}}$, if they maintain high levels of physical activity.²³ In
226 addition to her past and actual training program, DL's level of physical training is evidenced
227 by her very low body fat content ($\sim 15\%$) in comparison to reference values in elderly females
228 ($\sim 40\%$).²⁴ DL's physiological age for HR_{max} (~ 74 years) was slightly lower than her biological
229 age (83 years). The high $\text{VO}_{2\text{max}}$ and HR_{max} level explained the high value of O_2 pulse,
230 corresponding to the mean values reported in a population in the 5th decade.²⁵ It is worth noting
231 that O_2 pulse increased almost linearly during the treadmill test, indicating an absence of cardiac
232 ischemia.¹³ These observations attest the extremely well-preserved cardiovascular and
233 respiratory fitness of this master female athlete.

234
235 As shown by the T-scores and Z-scores for BMD, DL did not suffer from sarcopenia. However,
236 her muscle characteristics seemed to be similar or only slightly better than those generally
237 observed for her age and sex. DL's physiological age based on isokinetic strength (83 years)
238 was fairly similar to her biological age (83 years), but it was higher when based on her maximal
239 isometric strength (90 years). It is worth noting that the equation used to calculate DL's
240 physiological age only included females aged from 21 to 75 years, which may have led to an
241 overestimation of her physiological age. Indeed, an accelerated decline in physical performance
242 has been observed after approximately 80 years, suggesting that physiological functions decline
243 rapidly at around 80 years.²⁶ The study of DL's leg muscle volumes confirmed a potential
244 overestimation of her physiological age. Her thigh muscle volumes were fairly comparable with
245 those of older females aged ~ 72 years,¹⁹ showing that DL's muscle quantity was well-preserved
246 for her age. This preservation was more noticeable for the triceps surae, as it was 22% greater
247 than that of five Japanese females in the same age range.²⁰ Our observations regarding DL's
248 muscle function are in line with a recent meta-analysis⁹ in male master athletes competing in
249 endurance events, which showed that, in contrast to master strength/power athletes, chronic

250 endurance exercises did not prevent the loss of muscular strength. Chronic endurance training
251 therefore does not seem to prevent the age-related decline in muscular strength for either males
252 or females.

253
254 DL's BMD for the proximal femur region was within the osteopenia range, only revealing an
255 increased fracture risk. Therefore, DL did not have osteoporosis, despite the early menopause
256 and relatively low calcium intake, probably due to the regular training conducted over the
257 minimum effective amount shown to positively affect BMD [2.5 exercise sessions/week].²⁷
258 However, the Z-scores at the proximal femur region (0.7) showed that DL's BMD was clearly
259 similar to that of females of the same age. This result confirms that post-menopausal female
260 master runners do not seem to benefit from specific bone protection.¹²

261 262 **CONCLUSION**

263 The present single case study of a master female runner shows that remarkable cardiorespiratory
264 fitness, associated with long-term endurance training, is not associated with a specific
265 preservation of muscle and skeletal characteristics.

266 267 **PRACTICAL APPLICATIONS**

268 The results of this study do not support the use of highly intensive aerobic training to prevent
269 age-related declines in muscle strength and bone quality in females.

270 271 **CONFLICTS OF INTEREST**

272 All authors declare no conflicts of interest.
273

274 275 **REFERENCES**

- 276 1. Tanaka H, Seals DR. Endurance exercise performance in Masters athletes: age-associated changes and
277 underlying physiological mechanisms. *J Physiol*. 2008;586(1):55-63. doi:10.1113/jphysiol.2007.141879
- 278 2. Webb JL, Uner SC, McDaniels J. Physiological Characteristics of a Champion Runner: Age 77. *J*
279 *Gerontol*. 1977;32(3):286-290. doi:10.1093/geronj/32.3.286
- 280 3. Trappe S, Hayes E, Galpin A, et al. New records in aerobic power among octogenarian lifelong
281 endurance athletes. *J Appl Physiol*. 2013;114(1):3-10. doi:10.1152/jappphysiol.01107.2012
- 282 4. Kaminsky LA, Imboden MT, Arena R, Myers J. Reference Standards for Cardiorespiratory Fitness
283 Measured With Cardiopulmonary Exercise Testing Using Cycle Ergometry: Data From the Fitness
284 Registry and the Importance of Exercise National Database (FRIEND) Registry. *Mayo Clin Proc*.
285 2017;92(2):228-233. doi:10.1016/j.mayocp.2016.10.003
- 286 5. Karlsen T, Leinan IM, Bækkerud FH, et al. How to Be 80 Year Old and Have a VO_{2max} of a 35 Year
287 Old. *Case Rep Med*. 2015;2015:1-6. doi:10.1155/2015/909561
- 288 6. Lepers R, Stapley PJ, Cattagni T, Gremeaux V, Knechtle B. Limits in endurance performance of
289 octogenarian athletes. *J Appl Physiol*. 2013;114(6):829. doi:10.1152/jappphysiol.00038.2013
- 290 7. Wiswell RA, Jaque S V, Marcell TJ, et al. Maximal aerobic power, lactate threshold, and running
291 performance in master athletes. *Med Sci Sports Exerc*. 2000;32(6):1165-1170. doi:10.1097/00005768-
292 200006000-00021
- 293 8. Vaitkevicius P V, Fleg JL, Engel JH, et al. Effects of age and aerobic capacity on arterial stiffness in
294 healthy adults. *Circulation*. 1993;88(4 Pt 1):1456-1462. <http://www.ncbi.nlm.nih.gov/pubmed/8403292>.
295 Accessed July 3, 2018.
- 296 9. Mckendry J, Breen L, Shad BJ, Greig CA. Muscle morphology and performance in master athletes: A
297 systematic review and meta-analyses. *Ageing Res Rev*. 2018;45:62-82. doi:10.1016/j.arr.2018.04.007
- 298 10. Hansen M, Kjaer M. Influence of Sex and Estrogen on Musculotendinous Protein Turnover at Rest and
299 After Exercise. *Exerc Sport Sci Rev*. 2014;42(4):183-192. doi:10.1249/JES.0000000000000026
- 300 11. Wiswell RA, Hawkins SA, Dreyer HC, Jaque S V. Maintenance of BMD in Older Male Runners Is
301 Independent of Changes in Training Volume or VO_{2peak}. *Journals Gerontol Ser A Biol Sci Med Sci*.
302 2002;57(4):M203-M208. doi:10.1093/gerona/57.4.M203
- 303 12. Hawkins SA, Wiswell RA, Jaque S V, et al. The inability of hormone replacement therapy or chronic
running to maintain bone mass in master athletes. *J Gerontol A Biol Sci Med Sci*. 1999;54(9):M451-5.

304 <http://www.ncbi.nlm.nih.gov/pubmed/10536648>. Accessed July 20, 2018.

305 13. Belardinelli R, Lacalaprice F, Carle F, et al. Exercise-induced myocardial ischaemia detected by
306 cardiopulmonary exercise testing. *Eur Heart J*. 2003;24(14):1304-1313.
307 <http://www.ncbi.nlm.nih.gov/pubmed/12871687>. Accessed September 14, 2018.

308 14. Oliveira RB, Myers J, Araújo CGS, Abella J, Mandic S, Froelicher V. Maximal exercise oxygen pulse as
309 a predictor of mortality among male veterans referred for exercise testing. *Eur J Cardiovasc Prev
310 Rehabil*. 2009;16(3):358-364. doi:10.1097/HJR.0b013e3283292fe8

311 15. Tanaka H, Monahan KD, Seals DR. Age-predicted maximal heart rate revisited. *J Am Coll Cardiol*.
312 2001;37(1):153-156. <http://www.ncbi.nlm.nih.gov/pubmed/11153730>. Accessed September 7, 2018.

313 16. Myers J, Kaminsky LA, Lima R, Christle JW, Ashley E, Arena R. A Reference Equation for Normal
314 Standards for VO2 Max: Analysis from the Fitness Registry and the Importance of Exercise National
315 Database (FRIEND Registry). *Prog Cardiovasc Dis*. 2017;60(1):21-29.
316 doi:10.1016/J.PCAD.2017.03.002

317 17. Harbo T, Brincks J, Andersen H. Maximal isokinetic and isometric muscle strength of major muscle
318 groups related to age, body mass, height, and sex in 178 healthy subjects. *Eur J Appl Physiol*.
319 2012;112(1):267-275. doi:10.1007/s00421-011-1975-3

320 18. Neder JA, Nery LE, Shinzato GT, Andrade MS, Peres C, Silva AC. Reference Values for Concentric
321 Knee Isokinetic Strength and Power in Nonathletic Men and Women from 20 to 80 Years Old. *J Orthop
322 Sport Phys Ther*. 1999;29(2):116-126. doi:10.2519/jospt.1999.29.2.116

323 19. Maden-Wilkinson TM, McPhee JS, Rittweger J, Jones DA, Degens H. Thigh muscle volume in relation
324 to age, sex and femur volume. *Age (Dordr)*. 2014;36(1):383-393. doi:10.1007/s11357-013-9571-6

325 20. Csapo R, Malis V, Sinha U, Du J, Sinha S. Age-associated differences in triceps surae muscle
326 composition and strength – an MRI-based cross-sectional comparison of contractile, adipose and
327 connective tissue. *BMC Musculoskelet Disord*. 2014;15(1):209. doi:10.1186/1471-2474-15-209

328 21. Kanis JA, McCloskey E V., Johansson H, Oden A, Melton LJ, Khaltsev N. A reference standard for the
329 description of osteoporosis. *Bone*. 2008;42(3):467-475. doi:10.1016/J.BONE.2007.11.001

330 22. Williams CJ, Williams MG, Eynon N, et al. Genes to predict VO2max trainability: a systematic review.
331 *BMC Genomics*. 2017;18(Suppl 8):831. doi:10.1186/s12864-017-4192-6

332 23. Hagberg J. Effect of training on the decline of VO2max with aging. *Fed Proc*. 1987;46(5):1830-1833.
333 <https://europepmc.org/abstract/med/3556603>. Accessed March 19, 2019.

334 24. Pedersen AN, Ovesen L, Schroll M, Avlund K, Era P. Body composition of 80-years old men and
335 women and its relation to muscle strength, physical activity and functional ability. *J Nutr Health Aging*.
336 2002;6(6):413-420. <http://www.ncbi.nlm.nih.gov/pubmed/12459892>. Accessed March 19, 2019.

337 25. Oliveira RB, Myers J, Araújo CGS de. Long-term stability of the oxygen pulse curve during maximal
338 exercise. *Clinics (Sao Paulo)*. 2011;66(2):203-209. doi:10.1590/S1807-59322011000200004

339 26. Knechtle B, Kohler G, Rosemann T. Study of a European male champion in 10-km road races in the age
340 group >85 years. *Proc (Bayl Univ Med Cent)*. 2010;23(3):259-260.
341 <http://www.ncbi.nlm.nih.gov/pubmed/20671823>. Accessed September 14, 2018.

342 27. Kemmler W, von Stengel S, Kohl M. Exercise Frequency and Fracture Risk in Older Adults—How
343 Often Is Enough? *Curr Osteoporos Rep*. 2017;15(6):564-570. doi:10.1007/s11914-017-0407-7

344

345