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Force-Velocity Profile in sprinting: sex effect

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Abstract

The ability to produce muscle power during sprint acceleration is a major determinant of physical performance. The comparison of the force-velocity (F-v: theoretical maximal force, F_0 ; velocity, v_0 and maximal power output, P_{max}) profile between men and women has attracted little attention. Most studies of sex differences have failed to apply a scaling ratio when reporting data. The present study investigated the sex effect on the F-v profile using an allometric model applied with body mass (BM), fat-free mass (FFM), fat-free mass of the lower limb (FFMLL), cross-sectional area (CSA) and leg length (LL) to mechanical parameters. Thirty students (15 men, 15 women) participated. Raw velocity-time data for three maximal 35m sprints were measured with a radar. Mechanical parameters of the F-v relationship were calculated from the modelling of the velocity-time curve. When F_0 and P_{max} were allometrically scaled with BM ($p = 0.538$; ES = 0.23) and FFM ($p = 0.176$; ES = 0.51), there were no significant differences between men and women. However, when the allometric model was applied to P_{max} with FFMLL ($p = 0.015$; ES = 0.52), F_0 with CSA ($p = 0.016$; ES = 0.93) and v_0 with LL ($p \leq 0.001$; ES = 1.98) differences between men and women persisted. FFM explained 83% of the sex differences in the F-v profile ($p \leq 0.001$). After applying an allometric model, sex differences in the F-v profile are explained by other factors than body dimensions (*i.e.*, physiological qualitative differences).

Keywords Sex, Force, Velocity, Allometric model, Sprint

Abbreviations

BM (kg):	Body mass
CSA:	Cross-sectional area
D_{RF} (%.s/m):	Rate of decrease in ratio of force
F_0 (N):	Theoretical maximal force
FFM (kg):	Fat-free mass
FFMLL (kg):	Fat-free mass of the lower limb
F-v:	Force-velocity
LL:	Leg length
P_{max} (W):	Maximal power output
RF_{max} (%):	Maximal value of the ratio of force
S_{FV} (N.s/m):	Slope of the force-velocity profile
v_0 (m/s):	Theoretical maximal velocity

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35 Introduction

36 The ability to produce high muscle power during jumps or sprints is one of the major determinants of
37 physical performance in most sport disciplines (Morin and Samozino 2016). This power is produced from the force
38 and velocity components and depends on athletes' neuromuscular and osteoarticular systems (Morin and Samozino
39 2016). The horizontal force-velocity profile (F-v) in sprinting provides information on the specific acceleration
40 movement and on the underlying physical or technical characteristics that limit the performance of each individual
41 in sprinting (Samozino et al. 2016). The power-force-velocity profiling approach is based on the F-v and power-
42 velocity relationships characterizing the maximal mechanical capabilities of the neuromuscular system of the
43 lower limbs. However, age, performance level, technique, and sex are factors that influence the F-v profile (Mirkov
44 et al. 2020). For any given level of training, men display higher force, velocity, and power capacities than women
45 (Cheuvront et al. 2005; Cardoso de Araújo et al. 2020; Mirkov et al. 2020). The analysis of the F-v profile has
46 been linked to training interventions, performance, and injury prevention (Samozino et al. 2012; Morin et al.
47 2015a; Edouard et al. 2016), but the comparison of profiles between men and women has attracted little attention.
48 Moreover, a recent review has identified some sex differences in running related to biomechanical, physiological,
49 and neuromuscular aspects (Besson et al. 2022).

50 Only a few studies have compared the parameters of the F-v profile in sprinting between men and women
51 (Slawinski et al. 2017; Jiménez-Reyes et al. 2019; Devismes et al. 2019; Nuell et al. 2019; Haugen et al. 2020;
52 Mirkov et al. 2020). The majority of these studies indicated that men have higher values of maximal power output
53 (P_{\max}), theoretical maximal force (F_0) and theoretical maximal velocity (v_0) compared to women. All these sex
54 differences could have different explanations. Some authors have proposed some quantitative factors (absolute
55 muscle mass in men, smaller skeletons and higher percentage of body fat in women) to explain these sex
56 differences (Cheuvront et al. 2005; Perez-Gomez et al. 2008). These anthropometric and body composition
57 differences could lead to differences in the ability to generate forward acceleration, reach maximum speed, and be
58 able to maintain it for as long as possible. To neutralize the effect of anthropometric parameters, an allometric
59 model must usually be applied as the mathematical method (Jaric et al. 2005). Indeed, a well-known physiological
60 principle states that muscle strength or power production capabilities do not increase linearly with increasing body
61 mass (BM) (Jaric et al. 2005). The allometric model allows for a more appropriate account of differences in body
62 size (Nedeljkovic et al. 2009). However, most studies of sex differences have not been able to report data using an
63 allometric model (Jiménez-Reyes et al. 2019; Devismes et al. 2019; Haugen et al. 2019, 2020; Nuell et al. 2019).
64 This can compromise comparisons between different studies since the effect of the quantitative dimensions of the
65 human body, between men and women, is not appropriately accounted for.

66 The results of Weber et al. (2006) showed that the differences between men and women in P_{\max} and mean
67 power of the lower limbs measured on a cycle ergometer disappeared with the application of an allometric model
68 with lean mass. However, when the allometric model was applied with the lean mass of the lower limbs, differences
69 between sex persisted. It is also worth recalling the work of Vandewalle et al. (1985) who showed, on a cycle
70 ergometer, that the sex differences in the F-v parameters relative to BM could be explained by body dimensions,
71 suggesting that men and women differed in lean body weight and height but had the same muscle properties.
72 Nevertheless, the authors have not been able to report data using an allometric model. Regarding sprint running,
73 Slawinski et al. (2017) showed that there were still differences for F_0 after applying an allometric model with BM
74 (using 0.67 as theoretical exponent of BM). Mirkov et al. (2020) also applied an allometric model to P_{\max} and F_0
75 with BM using the theoretical exponent (0.67) to study the sex effect in sprinting. The differences between men
76 and women remained significant for P_{\max} and F_0 . These results suggest that factors other than BM may be
77 responsible for the higher muscle capacities observed in men. Moreover, BM might not be the most appropriate
78 scaling factor. For example, fat-free mass (FFM) is a more appropriate normalisation variable for performance
79 variables (Loftin et al. 2016) and considering the lean mass (or muscle volume) involved in exercise would be
80 even more accurate (Tolfrey et al. 2006).

81 Finally, very few studies have used the allometric model to study the effect of body dimensions between
82 men and women on the F-v parameters in sprinting (Slawinski et al. 2017; Mirkov et al. 2020). In addition, studies
83 that did use the allometric model did not include anthropometric variables allowing for more accurate
84 normalization (FFM and/or fat-free mass of the lower limb (FFMLL)) and only used the theoretical exponent of
85 BM (0.67). Absolute muscle mass and height could explain a high proportion of the differences between men and
86 women in the F-v profile (Cheuvront et al. 2005; Slawinski et al. 2017). However, on a cycle ergometer, these
87 differences are removed when an allometric model is applied with lean mass (Weber et al. 2006) and they
88 reappeared when the allometric model is applied with the lean mass of the lower limbs (Weber et al. 2006). In
89 sprinting the differences between men and women persist even when the allometric model is applied with BM
90 (Slawinski et al. 2017; Mirkov et al. 2020). It is therefore currently unclear whether the differences in mechanical

91 ability in sprinting are related to the normalization method or to other sex-specific parameters that influence the
92 F-v profile. Indeed, factors other than body dimensions (muscle properties, metabolic and enzymatic functioning)
93 may be able to explain sex differences in P_{\max} , force and velocity production in favour of men. Some authors have
94 suggested differences in enzymatic functioning and anaerobic capacity between men and women (Perez-Gomez
95 et al. 2008; Billaut and Bishop 2009). These sex differences may have an impact on the production of P_{\max} and the
96 subsequent ability to maintain power (Billaut and Bishop 2009). The existence of remaining differences in the
97 mechanical properties of sprinting after allometric modelling with some anthropometric variables would allow the
98 model to infer these differences to other parameters (qualitative and/or technical differences) (Weber et al. 2006).

99 In summary, most studies provide divergent results regarding the influence of anthropometric variables
100 in explaining sex differences in the F-v profile (Weber et al. 2006; Slawinski et al. 2017; Haugen et al. 2019; Nuell
101 et al. 2019; Mirkov et al. 2020). Moreover, the majority of studies were conducted with elite populations and very
102 few of them analysed recreational populations. To our knowledge, the allometric model has only been applied with
103 BM to study the effect of sex on the sprinting F-v profile. This study therefore aimed to investigate the effect of
104 sex on the F-v profile in recreational active men and women, using an allometric model applied with BM, FFM,
105 FFMLL, muscle cross-sectional area (CSA) and leg length (LL). We hypothesized that, when the allometric model
106 is applied to P_{\max} , F_0 and v_0 with anthropometric variables, significant differences exist between men and women.

108 **Materials and methods**

109 **Participants**

110 Thirty sports science healthy students, fifteen men (age: 24.1 ± 2.4 years; height: 180.0 ± 6.1 cm; BM:
111 71.5 ± 7.9 kg) and fifteen women (age: 22.9 ± 1.8 years; height: 170.0 ± 6.5 cm; BM: 61.3 ± 6.4 kg) participated
112 in this study. All subjects were physically active during the six months preceding the study and were engaged in
113 multisport activities, including sprints (e.g., football, rugby, ...), but were not sprint specialists. They performed
114 two to five hours of moderate physical activity three to five days a week but were not involved in systematic sports
115 training. The exclusion criteria were significant or systemic pathology and previous surgery on the lower limbs or
116 injuries identified in the three months preceding the tests.

118 **Experimental protocol**

119 Each subject conducted an experimental session including anthropometric measurements and an
120 assessment of the F-v profile. The protocol was approved by the ethical committee of sports sciences (CERSTAPS
121 n°IRB00012476-2021-21-10-132), and all subjects provided written informed consent to participate in the study.

123 **Procedures**

125 **Anthropometric measurements**

126 Height, sitting height and LL were determined using a stadiometer (0.1 cm, The Leicester Height
127 Measure, Tanita Corp., Japan) and BM was obtained using a clinical scale (0.1 kg, Tanita UM-076, Tanita Corp.,
128 Japan). Skinfolds at the sub-scapular, bicipital, tricipital, supra-iliac, quadricipital, hamstring and calf skinfolds
129 (posterior and lateral level) were measured to estimate the percentage of whole-body fat and lower limb body fat
130 using a Harpenden skinfold calliper (Baty International, England). Body density was calculated using the method
131 established by Durnin and Rahaman (1967) and body fat percentage was determined using the Siri equation (1956).
132 The total volume of the lower limb was calculated using the method of Jones and Pearson (1969). Lean volume of
133 the lower limb was expressed in kilograms to reflect FFMLL. Muscle CSA (cm^2) was estimated from the measured
134 thigh circumference at 2/3 of the distance from the patella to the greater trochanter and subsequently calculating
135 the surface area. Fat mass was considered by removing the fold measurement (in millimetres) from the thigh radius.

138 **F-v profile**

139 Each participant completed three sprints at maximum speed over a distance of 35 metres on a synthetic outdoor
140 field after a standardized 15-minute warm-up (Simperingham et al. 2019). It consisted of five minutes of low-
141 intensity running, several sprint-specific drills, and active-dynamic stretching. During the tests, the experimenter
142 signalled the start of each sprint using verbal instructions. Each subject wore their usual running shoes and set off

143 from a standing start to limit movements that could disrupt data acquisition. Between each sprint, a minimum
 144 recovery time of three minutes was set up. The best sprint time was retained for further investigations. The time
 145 was obtained using radar software (Stalker ATS 5.0). All sprints were carried out in favourable weather conditions
 146 (no wind).

147 The raw speed-time data were measured using a radar (Stalker ATS II, Applied Concepts, USA) at 46.875
 148 Hz. The radar was positioned five metres behind the starting line on a tripod and adjusted to the height of the
 149 subject's hips. The mechanical parameters of the F-v relationship were calculated from the modelling of the speed-
 150 time curve as proposed by Samozino et al. in 2016 (Samozino et al. 2016). Technical parameters such as the
 151 effective mechanical force *i.e.* the ratio of the horizontal force to the total force as a function of the speed of
 152 movement (D_{RF} *i.e.* the rate of decrease in the ratio of force) were determined (Samozino et al. 2016). D_{RF} was
 153 calculated over the entire acceleration phase via the linear relationship between the ratio of force and sprint speed.
 154 The maximal value of the ratio of force (RF_{max}) was also determined. The linear F-v relationships were extrapolated
 155 to determine the F_0 and v_0 values that correspond to the intersections with the force and velocity axes, respectively
 156 (Samozino et al. 2016). From the power-velocity curve, P_{max} (*i.e.*, the apex) was determined. The slope of the
 157 linear F-v relationship was calculated as follows (equation 1):

$$Sfv = -F_0/V_0 \quad (1)$$

158
 159
 160
 161 This variable represents the index of the athlete's individual balance between force and velocity
 162 capabilities. The steeper the slope, the more negative the value, the more "force-oriented" the F-v profile, and vice
 163 versa (Morin and Samozino 2016). This variable was calculated as it allows the determination of the mechanical
 164 F-v profile of the subjects. The raw acceleration data were processed in the radar software (Stalker ATS 5.0) by
 165 deleting all data recorded before the start and after the end of each sprint. Each acceleration file was then processed
 166 with a computer program (VBA, Microsoft Excel, USA) using the method of Samozino et al. (2016).
 167
 168

169 Allometric model

170 The method of power function adjustments (*i.e.*, the allometric model) was applied to P_{max} , F_0 and v_0 to
 171 study the sex effect. The allometric model was applied to P_{max} with BM, FFM and FFMLL. Indeed, muscular
 172 power output is proportional to the muscle CSA and fibre length and, consequently, proportional to the muscle
 173 volume or mass. Therefore, P_{max} should be related to active muscle volume or mass (Driss and Vandewalle 2013).
 174 According to the geometric similarity theory, the maximum force of the muscle is determined by the number of
 175 sarcomeres arranged in parallel and therefore is proportional to the CSA of the muscle (Åstrand and Rodahl 1986).
 176 The allometric model was therefore applied to F_0 with BM, FFM and CSA. Sprint speed is defined as the product
 177 of stride length and step frequency (Cheuvront et al. 2005). As sprint speed is affected by stride length and step
 178 frequency, longer LL may contribute to a longer stride that also leads to increased speed (Cheuvront et al. 2005;
 179 Nuell et al. 2019). Conversely, a shorter LL reduces the maximum stride length that can be achieved which in turn
 180 may decrease the maximum sprint speed (Brechue 2011; Slawinski et al. 2017). The allometric model was
 181 therefore applied to v_0 with LL. The allometric model adopted was based on the model proposed by Nevill and
 182 Holder (1995). The general form of the allometric relationship or power function is given by equation (2):

$$Y = a.X^b \quad (2)$$

183
 184
 185
 186 This equation describes a curvilinear relation where Y is the dependent variable (P_{max} , F_0 or v_0), a is the
 187 coefficient of proportionality, X is the variable of dimension (BM, FFM, CSA, FFMLL or LL) and b is the
 188 exponent (Nevill et al. 2005). The exponent b describes the relationship between the dependent variable and the
 189 independent variable, *i.e.*, the influence of the dimensional variable on the variable considered. The determination
 190 of the coefficients a and b is enabled using the method of least squares after applying a logarithmic transformation
 191 to the data. Equation 2 then becomes:

$$\log(Y) = \log(a) + b.\log(X) \quad (3)$$

192
 193
 194

195 Although the initial relation can be curvilinear, it becomes linear once the logarithmic transformation is
 196 applied. The exponent b (equation 2), which can be positive or negative, corresponds to the slope of this relation
 197 (equation 3). This then allows the calculation of the power function ratios in the form of Y/X^b , for example,
 198 P_{max}/BM^b (a variable that no longer considers body dimensions). All exponents b were determined for P_{max} with
 199 BM, FFM, FFMLL; F_0 with BM, FFM, CSA and v_0 with LL.

200
 201
 202

203 Statistical analysis

204 To analyse the sex effect between men and women, an independent-sample t-test was used to compare all
 205 the variables. The data distributions were assessed using the Shapiro-Wilk normality test and the homogeneity of
 206 the variances was assessed by Levene's test. Cohen's d effect sizes (ES) were calculated (rank biserial correlation
 207 for non-parametric variables). Thresholds of 0.2, 0.5, and 0.8 were defined as small, moderate, and large effects
 208 (Cohen 1988). An allometric model applied to P_{max} with BM, FFM, FFMLL, F_0 with BM, FFM, CSA and v_0 with
 209 LL was used to study the effect of sex. Descriptive data are presented as mean \pm standard deviation.

210 A stepwise multiple linear regression was used to assess the linear relationships between the dependent
 211 variable (P_{max}) and the independent variables (BM, FFM, FFMLL, BMI, whole-body fat, and sex). The 95%
 212 confidence intervals were determined. Statistical analysis was performed using RStudio 2 software version
 213 1.2.5033 (R Studio Team, 2019) and the risk α was set at 5%, i.e., $P \leq 0.05$.

214
 215

216 Results

217 Absolute P_{max} , F_0 , and v_0 were significantly higher in men than in women. When F_0 and P_{max} were
 218 allometrically scaled with BM and FFM, there were no significant differences between men and women. However,
 219 when the allometric model was applied to P_{max} with FFMLL, F_0 with CSA and v_0 with LL, differences between
 220 men and women persisted. Sprint time was significantly better in men than in women ($5.3 \pm 0.3s$ vs $6.3 \pm 0.6s$).

221
 222

222 Anthropometric parameters

223 Table 1 presents descriptive data and sex comparisons for the anthropometric characteristics of the
 224 subjects.

225
 226

Table 1 Comparison of anthropometric characteristics according to sex

Variables (mean \pm SD)	Men (n = 15)	Women (n = 15)	p-Value	ES
Age (years)	24.1 \pm 2.4	22.9 \pm 1.8	0.221	0.27
BM (kg)	71.5 \pm 7.9	61.3 \pm 6.4	< 0.001 *	1.37
Height (cm)	180.0 \pm 6.1	170.0 \pm 6.5	< 0.001 *	2.05
LL (cm)	88.6 \pm 3.7	82.1 \pm 7.8	0.002 *	0.67
BMI	22.1 \pm 2.3	21.9 \pm 1.8	0.879	0.06
Whole-body fat (%)	12.4 \pm 3.6	25.5 \pm 4.2	< 0.001 *	3.34
Lower limb body fat (%)	15.4 \pm 4.5	30.6 \pm 4.6	< 0.001 *	3.28
FFM (kg)	62.4 \pm 6.7	45.4 \pm 4.4	< 0.001 *	3.02
FFMLL (kg)	9.1 \pm 1.4	7.4 \pm 1.4	0.002 *	1.23
CSA (cm ²)	207.9 \pm 30.5	186.1 \pm 31.4	0.064	0.70

* $P < 0.05$

227 BM, body mass; LL, leg length; BMI, body mass index; FFM, fat-free mass; FFMLL, fat-free mass of the lower
 228 limb; CSA, cross-sectional area. FFM and FFMLL include lean, water, and bone mass.

229 BM, height, LL, FFM, fat-free volume of the lower limb, and FFMLL were significantly higher in men
 230 than in women. Whole-body fat and lower limb body fat were significantly lower in men than in women. Age,
 231 BMI, and CSA were not significantly different between sex.

232

233 **F-v parameters**

234 Table 2 presents sex comparisons of P_{\max} parameters expressed in absolute terms, ratio-scaled, and
 235 allometrically scaled to BM, FFM, and FFMLL.

237 **Table 2** Comparison of allometrically transformed P_{\max} parameters according to sex

Variables (<i>mean ± SD</i>)	Men (n = 15)	Women (n = 15)	p-Value	ES
P_{\max} (W)	1090.3 ± 258.7	674.7 ± 155.3	< 0.001 *	1.95
P_{\max} /BM (W.kg ⁻¹)	15.1 ± 2.2	11.1 ± 2.3	< 0.001 *	1.77
P_{\max} /BM ^{1.91}	0.3 ± 0.0	0.3 ± 0.1	0.077	0.38
P_{\max} /FFM (W.kg ⁻¹)	17.3 ± 2.6	14.8 ± 2.8	0.017 *	0.93
P_{\max} /FFM ^{1.56}	1.7 ± 0.2	1.7 ± 0.3	0.820	0.05
P_{\max} /FFMLL (W.kg ⁻¹)	120.0 ± 24.7	94.4 ± 26.2	0.021 *	0.49
P_{\max} /FFMLL ^{0.98}	125.9 ± 25.8	98.5 ± 27.1	0.015 *	0.52

* $P < 0.05$

238 P_{\max} , maximal power output; BM, body mass; FFM, fat-free mass; FFMLL, fat-free mass of the lower limb. FFM
 239 and FFMLL include lean, water, and bone mass. FFMLL was computed only for the right leg.

240 Absolute, relative P_{\max} to BM, FFM and FFMLL were significantly higher in men than in women. With
 241 the allometric model applied to BM and FFM, sex differences disappeared. These differences persisted with the
 242 allometric model applied with FFMLL.

244 Table 3 presents sex comparisons of F_0 and v_0 parameters expressed in absolute terms, ratio-scaled, and
 245 allometrically scaled to BM, FFM, CSA and LL, respectively.

246 **Table 3** Comparison of allometrically transformed F_0 and v_0 parameters according to sex

Variables (<i>mean ± SD</i>)	Men (n = 15)	Women (n = 15)	p-Value	ES
F_0 (N)	506.2 ± 105.9	390.4 ± 75.6	0.002 *	1.26
F_0 /BM (N.kg ⁻¹)	7.0 ± 0.9	6.4 ± 0.9	0.045 *	0.77
F_0 /BM ^{1.48}	0.9 ± 0.1	0.9 ± 0.1	0.538	0.23
F_0 /FFM (N.kg ⁻¹)	8.1 ± 1.1	8.6 ± 1.1	0.222	0.46
F_0 /FFM ^{1.02}	7.4 ± 1.0	7.9 ± 1.0	0.176	0.51
F_0 /CSA (N/cm ²)	2.4 ± 0.4	2.1 ± 0.3	0.025 *	0.86
F_0 /CSA ^{0.91}	3.9 ± 0.7	3.3 ± 0.5	0.016 *	0.93
v_0 (m.s ⁻¹)	8.6 ± 0.6	6.9 ± 0.8	< 0.001 *	2.49
V_{opt} (m.s ⁻¹)	4.3 ± 0.3	3.5 ± 0.4	< 0.001 *	2.49
V_{max} (m.s ⁻¹)	8.3 ± 0.5	6.7 ± 0.7	< 0.001 *	0.95
v_0 /LL (1/s)	9.7 ± 0.8	8.5 ± 1.4	0.028 *	0.48
v_0 /LL ^{0.31}	8.9 ± 0.6	7.4 ± 0.9	< 0.001 *	1.98

* $P < 0.05$

248 F_0 , theoretical maximal force; BM, body mass; FFM, fat-free mass; CSA, cross-sectional area; v_0 , theoretical
 249 maximum velocity; V_{opt} , optimal velocity; V_{max} , maximal velocity; LL, leg length. FFM includes lean, water,
 250 and bone mass.

251 Absolute and relative F_0 to BM were significantly higher in men than in women. There were no significant
 252 differences when F_0 was normalized to FFM. With the allometric model applied to BM and FFM, sex differences
 253 disappeared. These differences persisted with F_0 relative to CSA and with the allometric model applied with CSA.
 254 All velocity parameters were significantly higher for men than for women.

256 **Slope and mechanical parameters of the force-velocity profile and sprint time**

257 Table 4 presents descriptive data and sex comparisons for the slope and mechanical parameters of the F-
 258 v profile and sprint time.

259

260 **Table 4** Comparison of slope and mechanical parameters of the force-velocity profile and sprint time according
 261 to sex

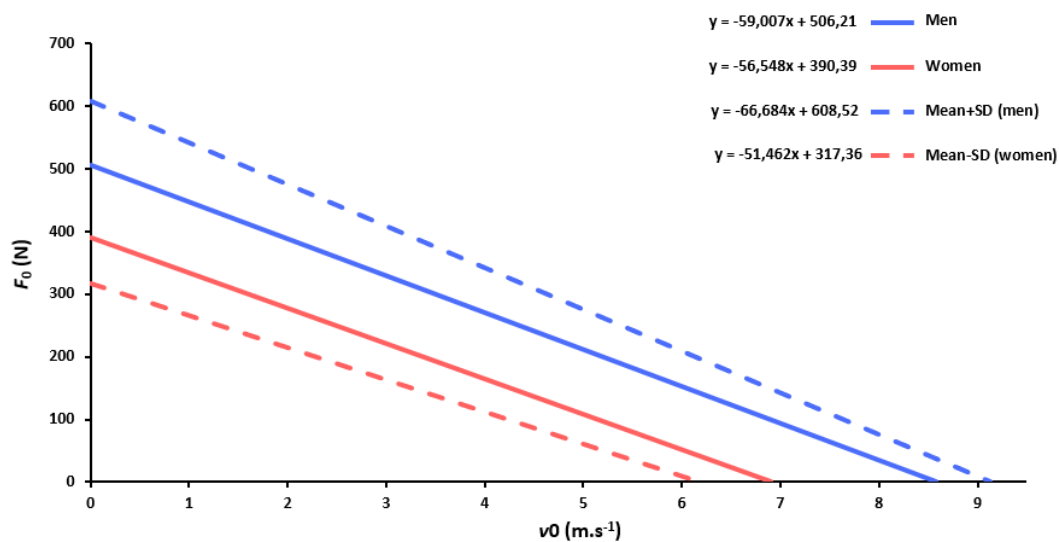
Variables (mean ± SD)	Men (n = 15)	Women (n = 15)	p-Value	ES
S_{FV} (N.s/m)	- 59.0 ± 11.6	- 57.1 ± 12.3	0.671	0.16
S_{FV} (N/kg.s/m)	- 0.82 ± 0.12	- 0.93 ± 0.11	0.026 *	0.86
S_{FV} (N/kg.s/m)	- 0.95 ± 0.15	- 1.25 ± 0.18	< 0.001 *	1.83
S_{FV} (N/cm ² .s/m)	- 0.29 ± 0.05	- 0.31 ± 0.05	0.232	0.45
RF_{max} (%)	48.1 ± 3.6	43.3 ± 3.9	0.002 *	1.27
D_{RF} (%.s/m)	- 7.6 ± 1.1	- 8.8 ± 1.0	0.004 *	1.15
Time (s)	5.3 ± 0.3	6.3 ± 0.6	< 0.001 *	0.93

* $P < 0.05$

262 S_{FV} , force-velocity slope; RF_{max} , maximum value of ratio of force; D_{RF} , decrement in ratio of force.

263 The slope of the force-velocity relationship (S_{FV}) was not significantly different between men and women
 264 when F_0 was in absolute value (Figure 1) and relative to CSA. However, S_{FV} was significantly different between
 265 men and women when F_0 was relative to BM and FFM. RF_{max} was significantly higher and D_{RF} significantly less
 266 negative in men. Time was significantly lower for men than for women.

267



268 **Fig. 1** Force-Velocity relationship according to sex. Theoretical maximal force (F_0) and theoretical maximal
 269 velocity (v_0) values correspond to the intersections with the force and velocity axis, respectively. The blue line
 270 represents the average value for men and the red line represents the average value for women. The blue dotted line
 271 corresponds to the mean plus one standard deviation for men and the red dotted line corresponds to the mean minus
 272 one standard deviation for women.
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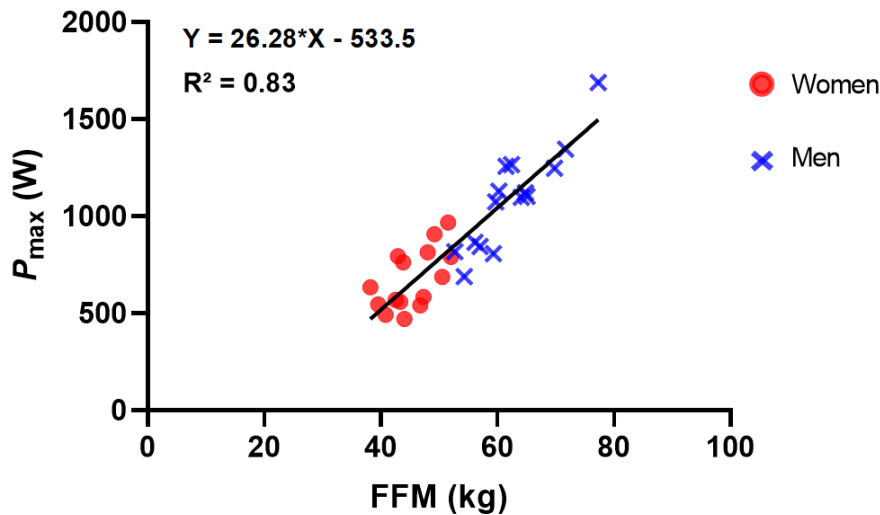
275

276 Parameters explaining P_{max}

277 Stepwise multiple linear regression showed that, in both men and women, P_{max} was significantly and
 278 positively associated with FFM ($b = 26.278$; 95% CI = [21.614; 30.941]; $p \leq 0.001$) (Figure 2). The coefficient of
 279 determination (R^2) was 0.83. The other independent variables were considered but did not contribute significantly
 280 to the model. They were therefore removed.

281

282



283

284 **Fig. 2** Linear relationship between maximum sprint power (P_{\max}) and fat-free mass (FFM)

285

286 Discussion

287 We aimed to investigate the effect of sex on the F-v profile in recreational active men and women, using
 288 an allometric model applied with BM, FFM, FFMLL, CSA and LL. We have hypothesized that, when the
 289 allometric model was applied to P_{\max} , F_0 and v_0 with anthropometric variables, significant differences existed
 290 between men and women. The main findings of this study confirmed our hypothesis. When F_0 and P_{\max} were
 291 allometrically scaled with BM and FFM, there were no significant differences between men and women. However,
 292 when the allometric model was applied to P_{\max} with FFMLL, F_0 with CSA and v_0 with LL, differences between
 293 men and women persisted. This study reinforces the fact that BM is not a relevant enough normalisation variable.
 294 Our results are consistent with previous reports (Loftin et al. 2016) indicating that considering the lean mass (or
 295 muscle volume) involved in exercise would be even more accurate (Tolfrey et al. 2006).

296

297 Comparison of allometric exponents

298 Our results are in contradiction with those of Slawinski et al. (2017) and Mirkov et al. (2020) since the
 299 differences between men and women for P_{\max} and F_0 persisted when using an allometric model applied with BM
 300 (0.67). This difference could be explained by the calculation of the exponents. In our study, we determined
 301 allometric exponents whereas the aforementioned studies (Slawinski et al. 2017; Mirkov et al. 2020) have used
 302 the theoretical BM exponent (0.67). However, we found similar results to those of Weber et al. (2006). They
 303 showed that the differences in power production on a cycle ergometer between men and women disappeared when
 304 an allometric model was applied to lean mass. Nevertheless, when they applied an allometric model to the active
 305 lean mass of the lower limbs, men produced significantly more P_{\max} (Weber et al. 2006). When we compared our
 306 BM exponent (1.91) for P_{\max} to this population (1.80) (Weber et al. 2006), the values were close indicating that
 307 BM has almost the same importance for P_{\max} in sprint running as sprint cycling. This is not the case for our
 308 exponents of FFM (1.56 vs 1.00) and FFMLL (0.98 vs 0.29). However, it should be noted that this study concerns
 309 sprints on a cycle ergometer and differs from the approach used in sprinting (*i.e.*, the horizontal profile) and in the
 310 task performed (cycling vs sprint running). Our results are difficult to compare with those already existing in the
 311 literature, as few studies have analysed the effect of sex in sprinting using the allometric model with FFM, FFMLL,
 312 CSA or LL. We also showed that exponents could be used to describe the allometric relationships between P_{\max} ,
 313 F_0 , and v_0 on the one hand, and their attributed dimensional variables on the other. Indeed, most exponents differed
 314 from the assumed exponent of 1.0 which is used when normalising the performance variable to the anthropometric
 315 variable and which assumes a linear relationship between the two variables (Weber et al. 2006). To the authors'
 316 knowledge, there are only two studies that have investigated the effect of sex on the F-v profile in sprinting using
 317 the allometric model (exponent of BM 0.67) (Slawinski et al. 2017; Mirkov et al. 2020). The comparison with
 318 these studies (Slawinski et al. 2017; Mirkov et al. 2020) is difficult since we did not use the theoretical exponent

319 (0.67). BM, FFM exponents for P_{\max} and BM exponent for F_0 were all greater than 1.0 indicating that P_{\max} and F_0
320 increased in greater proportions than the anthropometric variables. In contrast, the exponents of CSA for F_0 and v_0
321 for LL were less than 1.0 indicating that F_0 and v_0 did increase to a lesser extent than the anthropometric variable.
322 The identification of exponents different from 1.0 reinforces the argument that the outputs of P_{\max} , F_0 and v_0 do
323 not increase in direct proportion to BM, FFM, CSA and LL and therefore supports the use of an allometric model.
324 Conversely, FFMLL exponent for P_{\max} and FFM exponent for F_0 were very close to 1.0 indicating that F_0 and P_{\max}
325 values vary in the same proportions that the anthropometric variable, suggesting that the application of an
326 allometric model to P_{\max} with FFMLL and F_0 with FFM did not seem necessary with our population.

327

328 **F-v slopes according to sex in sprinting**

329 S_{FV} reflects the athlete's balance between force and velocity capabilities. Our results show that there are
330 no differences in the orientation of the F-v profile between men and women when the F-v slope is in absolute
331 values or normalised to F_0/CSA (N/cm^2). However, there are significant differences when the F-v slope is
332 expressed relative to BM and FFM. To the authors' knowledge, no study has expressed the F-v slope relative to
333 CSA or FFM. It is therefore difficult to compare this result with other studies. Many studies have reported
334 conflicting results for the F-v slope between sex. For example, Haugen et al. (2019) showed that the differences
335 in F-v slopes between men and women were small ($2.4 \pm 0.7\%$). Over several sport disciplines, S_{FV} values ranged
336 from -0.75 to $-1.10 N \cdot s^{-1} \cdot m^{-1} \cdot kg^{-1}$ for men and -0.80 to $-1.15 N \cdot s^{-1} \cdot m^{-1} \cdot kg^{-1}$ for women. Moreover, Mirkov et al.
337 (2020) showed negligible sex differences after allometric scaling with BM for S_{FV} between high-level sprinters.

338 Conversely, some studies have reported a more force-oriented profile in women than men. For example,
339 Devismes et al. (2019) observed that women have a significantly more negative S_{FV} than men for the same playing
340 level in soccer. The authors reported that a potential explanation for this observation could be sought in the average
341 sprint distance covered by the players. Jiménez-Reyes et al. (2019) compared the sprint mechanical F-v profile
342 between sex for soccer and futsal players of different levels. In futsal, women tend to have a F-v profile (relative
343 to BM) more force-oriented compared to men. In soccer, except when we compare the first division, women also
344 display a F-v profile (relative to BM) more force-oriented compared to men. However, the authors did not report
345 these variables' p-values. Haugen et al. (2020) quantified differences in sprint mechanical outputs in soccer
346 according to position, age, and sex on 674 men and women players. Women were generally more force-oriented
347 than men, by small but still most likely clear margins in terms of S_{FV} (Haugen et al. 2020). In opposition, Slawinski
348 et al. (2017) reported a significant velocity-oriented profile in world-class women compared to men on the
349 acceleration phase of a 100-metre sprint.

350 The divergent results reported among these studies could be due to the different sport disciplines
351 compared. Indeed, it has already been shown that sport discipline was associated with the orientation of the F-v
352 profile (Jiménez-Reyes et al. 2019; Haugen et al. 2019, 2020). The different normalisation methods used to express
353 S_{FV} values (absolute, relative to BM, and allometric scaling) may also explain the different results between studies.
354 The subjects in our study were not specialists in any sport. It is therefore consistent that there were no sex
355 differences in the orientation of the F-v profile.

356

357 **Factors explaining maximum power output in sprinting**

358 Anthropometric variables explain a significant proportion of the sex differences observed in P_{\max} . Indeed,
359 the stepwise multiple regression shows that FFM can explain 83% of the variance in P_{\max} . This result also means
360 that 17% of the variance in P_{\max} is not explained by FFM. Factors other than body dimensions (muscle properties,
361 metabolic and enzymatic functioning) may be able to explain the remaining variance in P_{\max} production. Even
362 after removing the influence of an anthropometric parameter (*i.e.*, FFMLL), men produced more P_{\max} than women.
363 These results are supported by the significant differences found for $F_0/CSA^{0.91}$ and $v_0/LL^{0.31}$. Since power is the
364 product of force and velocity, it is consistent to observe a significant difference in P_{\max} production between men
365 and women.

366 These sex differences in power, force and velocity production could be explained by factors that do not
367 depend on body dimensions. Some authors have suggested differences in enzymatic functioning and anaerobic
368 capacity between men and women (Perez-Gomez et al. 2008; Billaut and Bishop 2009). Although there are no
369 differences in the distribution of type II fibres, the area occupied by these fibres is higher in men than in women
370 (Jaworowski et al. 2002). Thus, the differences in anaerobic capacity could be explained by a higher proportion of
371 type II fibres in men. Even when this proportion of type II fibres was expressed to active muscle mass, the
372 differences remained (Perez-Gomez et al. 2008). It has also been reported that women have slower sarcoplasmic
373 reticulum calcium (Ca^{2+}) kinetics than men (24% lower peak sarcoplasmic reticulum Ca^{2+} ATPase activity)

374 (Hunter 2014). Slower Ca^{2+} ATPase activity and Ca^{2+} uptake into the sarcoplasmic reticulum are associated with
375 slower rates of relaxation and muscle mechanics (Hunter 2014). There are probably differences between men and
376 women in the subcellular aspects of muscle. These sex differences may have an impact on the production of P_{\max}
377 and the subsequent ability to maintain power (Billaut and Bishop 2009). Enzymatic factors could also explain
378 some of the differences in sprint power production between sex. Myosin ATP and creatine kinase activity have
379 been observed to be higher in men than in women (Borges and Essén-Gustavsson 1989) suggesting a greater
380 potential production of phosphagen energy in men to sustain the effort. The peak activity of the glycolytic and
381 glycogenolytic enzymes phosphofructokinase and lactate dehydrogenase is also lower in women (Billaut and
382 Bishop 2009). In addition, a smaller increase in plasma catecholamine concentration during sprints has also been
383 reported in women that may negatively influence the stimulation of glycolytic enzymes (Billaut and Bishop 2009).
384 These differences may affect sprint mechanics because glycolysis makes a significant contribution to ATP turnover
385 in the first few seconds of a maximal muscle contraction (Billaut and Bishop 2009). However, Jaworowski et al.
386 (2002) reported that higher peak glycolytic enzyme activities in men were related to height, mass, muscle CSA,
387 and relative type II fibre area, all of which were significantly greater in men than in women. It is therefore more a
388 factor of the larger body size of men than of the lower enzyme function of women. On the neuromuscular plan,
389 there may be differences between men and women during a sprint running task. However, little is known about
390 these differences and future research directly assessing these neuromuscular differences between sexes is therefore
391 necessary to move forward on this topic. In sum, factors that do not depend on body dimensions, such as metabolic
392 and enzymatic functioning, could explain the remaining 17% of the variance in P_{\max} and also contribute to sex
393 differences in P_{\max} , force and velocity production in favour of men.
394

395 **Technical parameters according to sex in sprinting**

396 Interestingly, our results also show that men can apply more force in the horizontal direction in the first
397 few metres of acceleration (higher RF_{\max}) and this decrease in RF_{\max} is less important with increasing running
398 velocity (less negative D_{RF}). Thus, men have better technical abilities than women in sprinting. Similar results
399 have already been reported previously (Devismes et al. 2019; Haugen et al. 2019; Jiménez-Reyes et al. 2020). To
400 our knowledge, two studies reported conflicting results. Mirkov et al. (2020) found similar D_{RF} values in high-
401 level sprinters. However, the number of women sprinters was relatively small compared to men (22 men vs 6
402 women) which limits the generalizability of these results. Zhang et al. (2020) found better D_{RF} values in women
403 compared to men but these results were in adolescent populations. The reasons for this better technical ability
404 remain unclear. It seems that this ability is related to the context of sprint training and that athletes trained in this
405 discipline demonstrate better D_{RF} values (Morin et al. 2011). However, none of the subjects was sprint specialists.

406 The importance of the role of the hip extensors, i.e. hamstrings and gluteal muscles in producing
407 horizontal force is well known (Morin et al. 2015b; Nuell et al. 2019). Interestingly, several studies have shown
408 that differences exist in the neuromuscular properties of hamstrings between men and women (Beaulieu et al.
409 2008; Blackburn et al. 2009; Bencke and Zebis 2011). For example, Janssen et al. (2014) reported that men had
410 favourable neuromuscular recruitment strategies compared to women (i.e. early activation of the biceps femoris
411 and semitendinosus). The neuromuscular capabilities of the hamstrings and gluteal muscles could therefore
412 underlie sex differences in horizontal force production. Women have been shown to have greater activation of the
413 quadriceps and lesser activation of the hamstrings compared to men during dynamic tasks (Malinzak et al. 2001;
414 Bencke and Zebis 2011; Williams and Welch 2015). These data agree with other studies that have shown women
415 to be 'quadriceps dominant' and less able to activate their hamstrings (Lephart et al. 2002; Hewett et al. 2005;
416 Youdas et al. 2007). Men are considered 'hamstring dominant' (Ebben et al. 2010) and have greater isometric and
417 eccentric (absolute and relative) knee flexor strength than women (Behan et al. 2019).

418 There are some methodological considerations to this study that should be noted. Firstly, the low level of
419 sprint-specific training in this population reduces the relevance of the results of the present study (e.g., for sprint
420 training) and limits the generalisation of these results to other populations. Secondly, although the majority of
421 participants were involved in multisport activities (including sprinting), participants who typically play team sports
422 such as soccer may have developed a greater sprinting ability than those who do not play such sports. This may
423 have impacted the ability to produce power as well as the ability to effectively apply horizontal force. However,
424 the fact that all participants were engaged in a different physical activity and were not sprint specialists also reduced
425 the impact of sport discipline on the F-v profile. Thirdly, the Samozino model did not allow us to measure RF_{\max}
426 directly. However, this model proposed and discussed by Samozino et al. (2016), is an accurate, reliable, and valid
427 simple method to evaluate mechanical properties of overground sprint running propulsion and it is validated
428 through a very good agreement with gold standard force plate measurements. The accuracy of the model can be
429 affected by the accuracy of the input data and the experimenter's data processing. We estimated the F-v profile
430 variables with a radar, which is a valid and reliable technology for measuring instantaneous velocity-time data
431 (Simperingham et al. 2016). Fourthly, the wind speed was not measured. However, all participants performed their

432 sprints in very similar conditions and with very light/no wind. The tests were always conducted when the wind
433 was neither from the front nor from the back. In addition, all measurements were carried out outdoors on a synthetic
434 field and without stands to again limit the effect of the wind (Haugen and Buchheit 2016). A potential light wind,
435 however, would only have a minimal influence on the force-velocity relationship and the power, force and velocity
436 assessments (Linthorne 1994; Ward-Smith 1999; Haugen and Buchheit 2016).

437 438 **Conclusion**

439 Our study confirms the importance of using an allometric model on the F-v profile in sprinting to study
440 the effect of sex. Anthropometric variables explain a significant proportion of the sex differences observed in P_{\max}
441 and factors that do not depend on body dimensions might be able to explain the remaining variance in P_{\max} . After
442 applying an allometric model, sex differences in the F-v profile are expected to be explained by other factors than
443 body dimensions (*i.e.*, metabolic, and enzymatic functioning) but evidence confirmed by non-invasive techniques
444 is needed. Sprinting is a key ability in many sports. A better understanding of sex-related differences in sprint
445 mechanics could be of importance in all sport disciplines. Although body size parameters present an important
446 contributing factor when observing differences in mechanical capacities between sex, physiological factors should
447 be considered when interpreting the findings obtained from the current study on men and women. Future studies
448 should confirm the physiological differences that may exist between men and women (*i.e.*, metabolic, enzymatic
449 functioning and neuromuscular function). Little is known about these differences and future research directly
450 assessing these qualitative differences between sex is, therefore, necessary to move forward on this topic.
451 Appropriate anthropometric variables for adjusting P_{\max} , F_0 and v_0 to body size are best derived through the process
452 of allometric scaling. Studies should use the allometric model to avoid the confounding effect of body dimensions.
453 FFM, FFMLL or CSA should also be used for more accurate normalisations when it is necessary.

454

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457

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459 experiments, analysed data, and interpreted the results of experiments. PG prepared figures and drafted the
460 manuscript. AS, NP, FB, CB, GD, and PD edited and revised the manuscript and approved the final version of it.

461

462 **Declarations**

463 **Conflict of Interest** The authors declare no conflict of interest, financial or otherwise.

464

465 **References**

466 Åstrand P-O, Rodahl K (1986) Textbook of Work Physiology: Physiological Bases of Exercise. McGraw
467 Hill

468 Beaulieu ML, Lamontagne M, Xu L (2008) Gender differences in time-frequency EMG analysis of
469 unanticipated cutting maneuvers. *Med Sci Sports Exerc* 40:1795–1804.
470 <https://doi.org/10.1249/MSS.0b013e31817b8e9e>

471 Behan FP, Moody R, Patel TS, et al (2019) Biceps femoris long head muscle fascicle length does not
472 differ between sexes. *J Sports Sci* 37:2452–2458.
473 <https://doi.org/10.1080/02640414.2019.1641016>

474 Bencke J, Zebis MK (2011) The influence of gender on neuromuscular pre-activity during side-cutting.
475 *J Electromyogr Kinesiol* 21:371–375. <https://doi.org/10.1016/j.jelekin.2010.10.008>

- 476 Besson T, Macchi R, Rossi J, et al (2022) Sex Differences in Endurance Running. *Sports Med.*
477 <https://doi.org/10.1007/s40279-022-01651-w>
- 478 Billaut F, Bishop D (2009) Muscle fatigue in males and females during multiple-sprint exercise. *Sports*
479 *Med* 39:257–278. <https://doi.org/10.2165/00007256-200939040-00001>
- 480 Blackburn JT, Bell DR, Norcross MF, et al (2009) Comparison of hamstring neuromechanical properties
481 between healthy males and females and the influence of musculotendinous stiffness. *J*
482 *Electromyogr Kinesiol* 19:362–369. <https://doi.org/10.1016/j.jelekin.2008.08.005>
- 483 Borges O, Essén-Gustavsson B (1989) Enzyme activities in type I and II muscle fibres of human skeletal
484 muscle in relation to age and torque development. *Acta Physiol Scand* 136:29–36.
485 <https://doi.org/10.1111/j.1748-1716.1989.tb08626.x>
- 486 Brechue W (2011) Structure-function Relationships that Determine Sprint Performance and Running
487 Speed in Sport. *IJASS(International Journal of Applied Sports Sciences)* 23:313–350.
488 <https://doi.org/10.24985/ijass.2011.23.2.313>
- 489 Cardoso de Araújo M, Baumgart C, Jansen CT, et al (2020) Sex differences in physical capacities of
490 german bundesliga soccer players. *J Strength Cond Res* 34:2329–2337.
491 <https://doi.org/10.1519/JSC.0000000000002662>
- 492 Chevront S, Carter R, Deruisseau K, Moffatt R (2005) Running performance differences between men
493 and women:an update. *Sports Med* 35:1017–1024. [https://doi.org/10.2165/00007256-](https://doi.org/10.2165/00007256-200535120-00002)
494 [200535120-00002](https://doi.org/10.2165/00007256-200535120-00002)
- 495 Cohen J (1988) *Statistical Power Analysis for the Behavioral Sciences*, Routledge
- 496 Devismes M, Aeles J, Philips J, Vanwanseele B (2019) Sprint force-velocity profiles in soccer players:
497 impact of sex and playing level. *Sports Biomech* 1–11.
498 <https://doi.org/10.1080/14763141.2019.1618900>
- 499 Driss T, Vandewalle H (2013) The measurement of maximal (anaerobic) power output on a cycle
500 ergometer: a critical review. *Biomed Res Int* 2013:589361.
501 <https://doi.org/10.1155/2013/589361>
- 502 Durnin JV, Rahaman MM (1967) The assessment of the amount of fat in the human body from
503 measurements of skinfold thickness. *Br J Nutr* 21:681–689.
504 <https://doi.org/10.1079/bjn19670070>
- 505 Ebben WP, Fauth ML, Petushek EJ, et al (2010) Gender-based analysis of hamstring and quadriceps
506 muscle activation during jump landings and cutting. *J Strength Cond Res* 24:408–415.
507 <https://doi.org/10.1519/JSC.0b013e3181c509f4>
- 508 Edouard P, Samozino P, Slotala R, et al (2016) Relation force–vitesse en sprint : perspectives dans le
509 suivi et la prévention des lésions musculaires des ischio-jambiers. *Journal de Traumatologie du*
510 *Sport* 33:177–181
- 511 Haugen T, Buchheit M (2016) Sprint Running Performance Monitoring: Methodological and Practical
512 Considerations. *Sports Med* 46:641–656. <https://doi.org/10.1007/s40279-015-0446-0>

- 513 Haugen TA, Breitschädel F, Seiler S (2020) Sprint mechanical properties in soccer players according to
514 playing standard, position, age and sex. *J Sports Sci* 38:1070–1076.
515 <https://doi.org/10.1080/02640414.2020.1741955>
- 516 Haugen TA, Breitschädel F, Seiler S (2019) Sprint mechanical variables in elite athletes: Are force-
517 velocity profiles sport specific or individual? *PLOS ONE* 14:0215551.
518 <https://doi.org/10.1371/journal.pone.0215551>
- 519 Hewett TE, Zazulak BT, Myer GD, Ford KR (2005) A review of electromyographic activation levels, timing
520 differences, and increased anterior cruciate ligament injury incidence in female athletes. *Br J*
521 *Sports Med* 39:347–350. <https://doi.org/10.1136/bjsm.2005.018572>
- 522 Hunter SK (2014) Sex differences in human fatigability: mechanisms and insight to physiological
523 responses. *Acta Physiol (Oxf)* 210:768–789. <https://doi.org/10.1111/apha.12234>
- 524 Janssen I, Steele JR, Munro BJ, Brown NAT (2014) Sex differences in neuromuscular recruitment are
525 not related to patellar tendon load. *Med Sci Sports Exerc* 46:1410–1416.
526 <https://doi.org/10.1249/MSS.0000000000000252>
- 527 Jaric S, Mirkov D, Markovic G (2005) Normalizing physical performance tests for body size: a proposal
528 for standardization. *J Strength Cond Res* 19:467–474. <https://doi.org/10.1519/R-15064.1>
- 529 Jaworowski A, Porter MM, Holmbäck AM, et al (2002) Enzyme activities in the tibialis anterior muscle
530 of young moderately active men and women: relationship with body composition, muscle
531 cross-sectional area and fibre type composition. *Acta Physiol Scand* 176:215–225.
532 <https://doi.org/10.1046/j.1365-201X.2002.t01-2-01004.x>
- 533 Jiménez-Reyes P, García-Ramos A, Cuadrado-Peñafiel V, et al (2019) Differences in Sprint Mechanical
534 Force-Velocity Profile Between Trained Soccer and Futsal Players. *Int J Sports Physiol Perform*
535 14:478–485. <https://doi.org/10.1123/ijsp.2018-0402>
- 536 Jiménez-Reyes P, Garcia-Ramos A, Párraga-Montilla JA, et al (2020) Seasonal Changes in the Sprint
537 Acceleration Force-Velocity Profile of Elite Male Soccer Players. *J Strength Cond Res*
- 538 Jones PR, Pearson J (1969) Anthropometric determination of leg fat and muscle plus bone volumes in
539 young male and female adults. *J Physiol* 204:63–66
- 540 Lephart SM, Ferris CM, Riemann BL, et al (2002) Gender differences in strength and lower extremity
541 kinematics during landing. *Clin Orthop Relat Res* 162–169. [https://doi.org/10.1097/00003086-](https://doi.org/10.1097/00003086-200208000-00019)
542 [200208000-00019](https://doi.org/10.1097/00003086-200208000-00019)
- 543 Linthorne NP (1994) The effect of wind on 100-m-sprint times. *Journal of applied biomechanics* 10:S.
544 110-131
- 545 Loftin M, Sothorn M, Abe T, Bonis M (2016) Expression of VO₂peak in Children and Youth, with Special
546 Reference to Allometric Scaling. *Sports Med* 46:1451–1460. [https://doi.org/10.1007/s40279-](https://doi.org/10.1007/s40279-016-0536-7)
547 [016-0536-7](https://doi.org/10.1007/s40279-016-0536-7)
- 548 Malinzak RA, Colby SM, Kirkendall DT, et al (2001) A comparison of knee joint motion patterns between
549 men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon)* 16:438–445.
550 [https://doi.org/10.1016/s0268-0033\(01\)00019-5](https://doi.org/10.1016/s0268-0033(01)00019-5)

- 551 Mirkov DM, Knezevic OM, Garcia-Ramos A, et al (2020) Gender-Related Differences in Mechanics of
552 the Sprint Start and Sprint Acceleration of Top National-Level Sprinters. *Int J Environ Res Public*
553 *Health* 17:6447
- 554 Morin J-B, Edouard P, Samozino P (2011) Technical ability of force application as a determinant factor
555 of sprint performance. *Med Sci Sports Exerc* 43:1680–1688.
556 <https://doi.org/10.1249/MSS.0b013e318216ea37>
- 557 Morin J-B, Gimenez P, Edouard P, et al (2015a) Sprint Acceleration Mechanics: The Major Role of
558 Hamstrings in Horizontal Force Production. *Front Physiol* 6:.
559 <https://doi.org/10.3389/fphys.2015.00404>
- 560 Morin J-B, Gimenez P, Edouard P, et al (2015b) Sprint Acceleration Mechanics: The Major Role of
561 Hamstrings in Horizontal Force Production. *Front Physiol* 6:404.
562 <https://doi.org/10.3389/fphys.2015.00404>
- 563 Morin J-B, Samozino P (2016) Interpreting Power-Force-Velocity Profiles for Individualized and Specific
564 Training. *International Journal of Sports Physiology and Performance* 11:267–272.
565 <https://doi.org/10.1123/ijsp.2015-0638>
- 566 Nedeljkovic A, Mirkov DM, Bozic P, Jaric S (2009) Tests of muscle power output: the role of body size.
567 *Int J Sports Med* 30:100–106. <https://doi.org/10.1055/s-2008-1038886>
- 568 Nevill AM, Bate S, Holder RL (2005) Modeling Physiological and Anthropometric Variables Known to
569 Vary with Body Size and Other Confounding Variables. *American Journal of Physical*
570 *Anthropology* 128:141–153. <https://doi.org/10.1002/ajpa.20356>
- 571 Nevill AM, Holder RL (1995) Scaling, normalizing, and per ratio standards: an allometric modeling
572 approach. *J Appl Physiol* (1985) 79:1027–1031. <https://doi.org/10.1152/jappl.1995.79.3.1027>
- 573 Nuell S, Illera-Domínguez V, Carmona G, et al (2019) Sex differences in thigh muscle volumes, sprint
574 performance and mechanical properties in national-level sprinters. *PLOS ONE* 14:0224862.
575 <https://doi.org/10.1371/journal.pone.0224862>
- 576 Perez-Gomez J, Rodriguez GV, Ara I, et al (2008) Role of muscle mass on sprint performance: gender
577 differences? *Eur J Appl Physiol* 102:685–694. <https://doi.org/10.1007/s00421-007-0648-8>
- 578 Samozino P, Rabita G, Dorel S, et al (2016) A simple method for measuring power, force, velocity
579 properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine*
580 *& Science in Sports* 26:648–658. <https://doi.org/10.1111/sms.12490>
- 581 Samozino P, Rejc E, Di Prampero PE, et al (2012) Optimal force-velocity profile in ballistic movements-
582 -altius: citius or fortius? *Med Sci Sports Exerc* 44:313–322.
583 <https://doi.org/10.1249/MSS.0b013e31822d757a>
- 584 Simperingham KD, Cronin JB, Pearson SN, Ross A (2019) Reliability of horizontal force-velocity-power
585 profiling during short sprint-running accelerations using radar technology. *Sports Biomech*
586 18:88–99. <https://doi.org/10.1080/14763141.2017.1386707>
- 587 Simperingham KD, Cronin JB, Ross A (2016) Advances in Sprint Acceleration Profiling for Field-Based
588 Team-Sport Athletes: Utility, Reliability, Validity and Limitations. *Sports Med* 46:1619–1645.
589 <https://doi.org/10.1007/s40279-016-0508-y>

- 590 Siri WE (1956) The Gross Composition of the Body. In: Lawrence JH, Tobias CA (eds) *Advances in*
591 *Biological and Medical Physics*. Elsevier, pp 239–280
- 592 Slawinski J, Termoz N, Rabita G, et al (2017) How 100-m event analyses improve our understanding of
593 worldclass men’s and women’s sprint performance. *Scand J Med Sci Sports* 27:45–54.
594 <https://doi.org/10.1111/sms.12627>
- 595 Tolfrey K, Barker A, Thom JM, et al (2006) Scaling of maximal oxygen uptake by lower leg muscle
596 volume in boys and men. *Journal of Applied Physiology* 100:1851–1856.
597 <https://doi.org/10.1152/jappphysiol.01213.2005>
- 598 Vandewalle H, Pérès G, Heller J, Monod H (1985) All out anaerobic capacity tests on cycle ergometers.
599 A comparative study on men and women. *Eur J Appl Physiol Occup Physiol* 54:222–229.
600 <https://doi.org/10.1007/BF02335934>
- 601 Ward-Smith AJ (1999) New insights into the effect of wind assistance on sprinting performance. *J*
602 *Sports Sci* 17:325–334. <https://doi.org/10.1080/026404199366037>
- 603 Weber CL, Chia M, Inbar O (2006) Gender differences in anaerobic power of the arms and legs--a
604 scaling issue. *Med Sci Sports Exerc* 38:129–137.
605 <https://doi.org/10.1249/01.mss.0000179902.31527.2c>
- 606 Williams DSB, Welch LM (2015) Male and female runners demonstrate different sagittal plane
607 mechanics as a function of static hamstring flexibility. *Braz J Phys Ther* 19:421–428.
608 <https://doi.org/10.1590/bjpt-rbf.2014.0123>
- 609 Youdas JW, Hollman JH, Hitchcock JR, et al (2007) Comparison of hamstring and quadriceps femoris
610 electromyographic activity between men and women during a single-limb squat on both a
611 stable and labile surface. *J Strength Cond Res* 21:105–111. [https://doi.org/10.1519/00124278-](https://doi.org/10.1519/00124278-200702000-00020)
612 [200702000-00020](https://doi.org/10.1519/00124278-200702000-00020)
- 613 Zhang Q, Pommerell F, Owen A, et al (2020) Running patterns and force-velocity sprinting profiles in
614 elite training young soccer players: A cross-sectional study. *European Journal of Sport Science*
615 0:1–9. <https://doi.org/10.1080/17461391.2020.1866078>
- 616