Sex-related differences in accumulated O2 deficit incurred by high-intensity rowing exercise during childhood and adolescence

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1   Original article

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4   **rowing exercise during childhood and adolescence**

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24   **Running title**: Accumulated O_2 deficit during growth

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37 **DECLARATIONS**

38 **Author contribution statement**

39 HM, CT and SR designed the research. JB, AD, HM, CT and SR collected the data and

40 performed the research. JB, AD, NA and SR analysed the data and supervised the research.

41 JB and SR wrote the manuscript. JB, HM, AD, NA, CT and SR provided critical revisions

42 important for intellectual content of the finished manuscript, approved the final version of the

43 manuscript, and agree to be accountable for all aspects of the work in ensuring that questions

44 related to the accuracy or integrity of any part of the work are appropriately investigated and

45 resolved. All persons designated as authors qualify for authorship, and all those who qualify

46 for authorship are listed.

47

48 **Ethics approval**

49 The present study was approved by an institutional ethics review board (Comité d'Éthique

50 pour la Recherche en Sciences et Techniques des Activités Physiques et Sportives –

51 CERSTAPS, n°2019-18-09-36) and conformed to the standards of use of human participants

52 in research as outlined in the *Sixth Declaration of Helsinki*.

53

54 **Consent to participate**

55 Written informed consent was obtained from all individual included in the study, and from

56 their parents or legal guardians.

57

58 **Consent for publication**

59 Participants (and their parents or legal guardians) signed informed consent regarding

60 publishing their data.

61

71 **Conflict of interest**

72 The authors declare no competing interests. The results of the study are presented clearly,

73 honestly and without fabrication, falsification or inappropriate data manipulation.

74

75 **ABSTRACT**

76 **Purpose**: The aims of the present study were to determine during childhood and adolescence

77 (i) the effect of sex on non-oxidative energy production, quantified by the accumulated

78 oxygen deficit (AOD), and (ii) the influence of AOD on high-intensity performance.

79 **Methods**: Thirty-nine boys and 35 girls aged 10-17 years performed a 60-s all-out test on a

80 rowing ergometer to determine AOD and mean power output (MPO). Multiplicative

81 allometric modelling was used to assess the concurrent effects of lean body mass (LBM) and

82 age on AOD.

83 **Results**: AOD significantly increased with age in both sexes ($p < 0.001$) with boys exhibiting

84 significantly higher AOD than girls from the age of 14 years (10-11.9 yr: 1.9 vs 1.9 L, 12-

85 13.9 yr: 2.4 vs 2.7 L, 14-15.9 yr: 2.8 vs 4.6 L and 16-17.9 yr: 2.9 vs 5.2 L, in girls and boys

86 respectively, $p < 0.001$). However, a sex difference was no longer significant when AOD was

87 analysed using an allometric model including age and LBM ($p = 0.885$). Finally, significant

88 correlations were found between AOD and MPO in boys and girls but with lower evidence in

89 girls ($r^2 = 0.41$ vs. 0.89).

90 **Conclusion**: Non-oxidative energy production increased more extensively in boys than girls

91 from the age of 14 years. Age and LBM accounted for the sexual differentiation of AOD

92 during childhood and adolescence. In addition, AOD was found to be a determinant factor of

93 high-intensity performance, more particularly in boys.

94

95 **KEY WORDS:** non-oxidative metabolism; lean body mass; girls; multiplicative allometric

96 modelling; age.

97

98 **ABBREVIATIONS**

99 ANCOVA   Analysis of covariance

100 ANOVA   Analysis of variance

101 AOD   Accumulated oxygen deficit

102 BM   Body mass

103 $[HCO_3^-]_{min}$ Minimal blood bicarbonate concentration

104 $[La]_{max}$ Maximal blood lactate concentration

105 LBM   Lean body mass

106 MPO   Mean power output

107 pH_{min} Minimal blood pH

108 $\dot{V}O_{2max}$ Maximal oxygen uptake

109 $\dot{V}O_{2rest}$ Oxygen uptake at rest

INTRODUCTION

It is well-established that the development of body composition during childhood and adolescence is sex-specific (Baxter-Jones et al. 2003; Wells 2007). Indeed, post-pubertal boys acquire a greater lean body mass (LBM) and less fat mass than post-pubertal girls during late adolescence (Baxter-Jones et al. 2003; Wells 2007). As fat is metabolically inert (Goran et al. 2000), this sexual dimorphism during puberty strongly influences performance during high-intensity exercise. For instance, peak power output (in W) increases significantly in both sexes from childhood into adolescence (Doré et al. 2001; Martin et al. 2003; Armstrong and Welsman 2019a) but from 13-14 years of age boys develop higher peak power output than girls (Blimkie et al. 1988; Armstrong et al. 1997; Martin et al. 2004; Doré et al. 2005; Mikulic and Markovic 2011; Armstrong and Welsman 2019a). Several authors have suggested that these differences in performance between girls and boys from the age of 13-14 years are influenced by non-oxidative energy output in addition to differences in body composition (Malina et al. 2004; Doré et al. 2005). However, while it is well-established that the contribution of non-oxidative metabolism during high-intensity exercise is greater in post- than pre-pubertal boys (Birat et al. 2018; Ratel et al. 2002b, a), no previous study has evaluated non-oxidative energy production during childhood and adolescence with respect to sex, or established any direct relationship between non-oxidative metabolism and performance during high-intensity exercise from childhood into adolescence.

The activity of non-oxidative metabolism can be assessed using several different methods such as muscle biopsy (Eriksson et al. 1971) or phosphorus[31] magnetic resonance spectroscopy (Tonson et al. 2010). However, for ethical or technological reasons, these techniques have not been used to evaluate the importance of non-oxidative metabolism in the relative development of the performance of girls and boys. Alternatively, blood lactate assays have been used to explore non-oxidative (glycolytic) metabolism during childhood and

135   adolescence, with only one study reporting a lower blood lactate response following maximal

136   exercise in girls compared to boys, from the age of 16 years (Cumming et al. 1985).

137   However, blood lactate concentration must be interpreted cautiously as lactate sampled in

138   blood cannot be assumed to reflect a consistent or direct relationship with muscle lactate

139   production. The physiological relevance of this blood marker to assess non-oxidative energy

140   turnover during high-intensity whole-body exercise is, therefore, highly debatable (Ferguson

141   et al. 2018).

142   Among other methods, the measurement of accumulated O_2 deficit (AOD) has been

143   found to be a valid technique in adults (Medbø et al. 1988) and children (Naughton and

144   Carlson 1995) to assess non-oxidative energy production during high-intensity, whole-body

145   exercise. However, use of this method with children and adolescents has seldom been

146   reported. To our knowledge, three studies have reported lower AOD, whether expressed in

147   absolute terms or in ratio with body mass (BM) in 9-12-year-old boys than male adolescents

148   or young men (Hebestreit et al. 1998; Leclair et al. 2011; Diry et al. 2020), thereby

149   suggesting an age effect on non-oxidative energy metabolism. Furthermore, while a sex-

150   related difference in AOD of ~15-25% (relative to body dimensions) has been observed in

151   adults (Medbø and Burgers 1990; Weyand et al. 1993; Ramsbottom et al. 1997; Weber and

152   Schneider 2000), no previous study has analysed changes in AOD during childhood and

153   adolescence with respect to sex. No differences in AOD or AOD relative to BM have been

154   reported during high-intensity exercise between 9-11-year-old non-athletic girls and boys

155   (Carlson and Naughton 1993; Naughton and Carlson 1995; Berthoin et al. 2003). In addition,

156   the only study to have analysed the sex-related difference in AOD in 14-15-year-olds showed

157   that trained girls (n = 8) had significantly lower absolute AOD and AOD relative to BM than

158   trained boys (n = 8) when exercising on an inclined treadmill at two constant exercise

159   intensities (120 and 130% of maximal aerobic power) (Naughton et al. 1997). These

160   differences were also found in performance, as running speed was significantly higher in

161   boys than girls at both exercise intensities (Naughton et al. 1997).

162   Although in previous studies AOD and performance during high-intensity exercise

163   have been occasionally investigated with small samples of girls and boys, a relationship

164   between metabolic and mechanical parameters has not been directly established (Carlson and

165   Naughton 1993; Naughton and Carlson 1995; Naughton et al. 1997). Leclair et al (2011)

166   reported a positive relationship between AOD relative to BM and time to exhaustion during a

167   cycle exercise at 100% of maximal aerobic power in 9-11-year-old boys; however, a similar

168   relationship was not observed in men.

169   However, interpretation of AOD is likely to have been clouded in previous studies

170   (Carlson and Naughton 1993; Naughton and Carlson 1995; Naughton et al. 1997; Hebestreit

171   et al. 1998; Berthoin et al. 2003; Leclair et al. 2011) by controlling for differences in body

172   size by simply dividing AOD by BM (i.e., ratio scaling). It is well-established that ratio

173   scaling with BM does not create size-free physiological variables during childhood and

174   adolescence (Welsman and Armstrong 2019). Numerous studies have demonstrated the

175   fallacy of ratio scaling physiological variables and it has been compellingly argued that with

176   cross-sectional data, allometric scaling based in log-linear regression with multiple covariates

177   is the method of choice when investigating the development of physiological variables during

178   growth (Nevill and Holder 1995; Welsman and Armstrong 2000, 2019). Furthermore, as fat

179   mass is metabolically inert (Goran et al. 2000), LBM is a more appropriate covariate of

180   physiological variables during exercise than total BM. LBM varies with age (Baxter-Jones et

181   al. 2003), therefore, allometric analyses including both age and LBM as covariates are likely

182   to provide more insights into AOD than ratio scaling with BM. Moreover, it has been

183   recently demonstrated with multiplicative allometric modelling of large, longitudinal data

184   sets of 11-18-year-olds that, in both sexes the most powerful influence on peak aerobic

185 power, peak power output, and mean power output is concurrent changes in age and LBM, as

186 reflected by the combination of BM and skinfold thicknesses (Armstrong and Welsman

187 2019a, b).

188   Therefore, the aims of the present study were to determine during childhood and

189 adolescence (i) the effect of sex on changes in non-oxidative metabolism (i.e., AOD) incurred

190 by high-intensity whole-body exercise, and (ii) the importance of AOD on performance with

191 respect to age and sex. We hypothesised that (i) AOD increases more extensively in boys

192 than in girls from the age of 14 years because of the greater gains in boys' LBM, (ii) sex-

193 related differences in AOD are not significant when changes in both age and LBM are taken

194 into account using a multiplicative allometric model, and (iii) non-oxidative energy

195 production (i.e., AOD) is positively associated with performance (i.e., power output) with the

196 relationship weaker in girls due to the smaller increase in their LBM.

197

198 **MATERIALS AND METHODS**

199 **Subjects**

200   Thirty-nine male and thirty-five female rowers aged from 10 to 17 years volunteered

201 to participate in the present study. All participants trained physically two to three times per

202 week with similar training volumes between girls and boys. None of the participants had a

203 family history of cardiovascular disease or was under medication. The present study was

204 approved by an institutional ethics review board (Comité d'Éthique pour la Recherche en

205 Sciences et Techniques des Activités Physiques et Sportives – CERSTAPS, n°2019-18-09-

206 36) and conformed to the standards of use of human participants in research as outlined in the

207 *Sixth Declaration of Helsinki*. The participants were informed of the experimental procedures

208 and gave their written assent before any testing was conducted. In addition, written informed

209 consent was obtained from the parents or legal guardians of the participants.

Experimental design

Volunteers were tested in two experimental sessions separated by at least 48 hours. Participants were instructed not to undertake any strenuous activity during the 24 hours preceding each session. The first session was dedicated to gathering participants' physical characteristics (anthropometric measurements and body composition) and maximal oxygen uptake ($\dot{V}O_{2max}$) assessment. During the second session, the volunteers performed a 60-s all-out test. The two exercise sessions were carried out on a rowing ergometer (Model D, Concept2, Morrisville, VT, USA). The young participants were fully familiarised with the equipment. The computer of the ergometer continuously delivered the power output (in W). The resistance factor was set by the investigators between 100 and 130 according to age, sex, and the expertise level of young rowers. The same resistance factor was kept for both tests. Verbal encouragement was systematically provided by the investigators during each exercise session.

Experimental measurements

Session 1

Anthropometric characteristics and body composition

BM (in kg) was measured using a digital weight scale with a precision of $\pm$ 0.01 kg (Seca 899, Seca, Germany). Standing height (in m) was assessed using a stadiometer with a precision of $\pm$ 1 mm (Seca 213, Seca, Germany). Skinfold thicknesses were measured at the triceps and subscapular sites using a Harpenden calliper (British Indicators Ltd, St Albans, UK) and the mean value from three reproducible measurements was calculated. The measurements were taken by the same experienced investigator on the right side of the body to reduce variability in the results for girls and boys. Body fat percentage and LBM (in kg) were determined using the equations developed by Slaughter et al. (1988). These equations

11

235   are specific to sex, ethnicity, and age, and are recommended for assessing body fat and LBM

236   in children 8-18 years of age.

237

238   *Maximal oxygen uptake test*

239   Each participant performed a progressive test to exhaustion to determine maximal O_2

240   uptake ($\dot{V}O_{2max}$ in $L \cdot min^{-1}$). The initial power was set between 40 and 80 W during the first

241   five minutes and the power was incremented by 10-30 W every three minutes according to

242   age, sex, and the expertise level of participants. Arterialised capillary blood samples (20 μL)

243   were taken from the earlobe at rest and every step to measure the time course of blood lactate

244   concentration ([La] in $mmol \cdot L^{-1}$). Whole blood [La] was determined enzymatically using a

245   Biosen C-Line Clinic lactate analyser (EFK Diagnostics GmbH, Barleben, Germany).

246   Oxygen uptake, carbon dioxide output and ventilation were continuously monitored

247   using a breath-by-breath analyser (Quark CPET, Cosmed, Italy). Heart rate was continuously

248   recorded with a heart rate monitor (HRM-Dual, Garmin, Kansas, USA). $\dot{V}O_{2max}$ was

249   considered to be reached during the last step when at least two of the following criteria were

250   met: (i) $\dot{V}O_2$ levelling-off, (ii) maximal respiratory exchange ratio ≥ 1.1, (iii) maximal heart

251   rate $\geq 95\%$ of the age-predicted maximal heart rate ($208.609 - 0.716 \cdot age$) (Shargal et al.

252   2015) and (iv) blood lactate concentration higher than 8 $mmol \cdot L^{-1}$.

253

254   **Session 2**

255   *60-s all-out test*

256   After a standardised 15-min warm-up at about 130-140 $beats \cdot min^{-1}$ and two short

257   sprints (10-s) in the last five minutes, all participants performed a 60-s all-out test. This test

258   was followed by a 10-min sitting recovery. Cardio-respiratory parameters were continuously

259   measured using a breath-by-breath analyzer (Quark CPET, Cosmed, Italy). Capillary

260   arterialised blood samples (80 µL) were drawn from the earlobe and collected after warm-up

261   and at 1-, 3-, 5-, and 8-min post-exercise to measure the time course of pH, bicarbonate

262   ($[HCO_3^-]$ in $mmol \cdot L^{-1}$) and lactate ($[La]$). Whole blood $[La]$ was determined enzymatically

263   using the same lactate analyser as in the first session while blood pH and $[HCO_3^-]$ were

264   measured by direct potentiometry using an i-STAT® handheld analyser (Abbott Point of

265   Care, Princeton, USA) immediately after collection. The maximal lactate concentration

266   ($[La]_{max}$), the minimal pH value (pH_{min}) and the minimal bicarbonate ions concentration

267   ($[HCO_3^-]_{min}$) were identified. Mean power output (MPO in W) was calculated over the entire

268   test and individual AOD (in L O_2 Eq.) was determined according to the procedure described

269   below.

270

271   **Measurements and calculations**

272   *Accumulated oxygen deficit*

273   AOD was determined by subtracting accumulated O_2 uptake (the measured O_2 uptake

274   integrated over time) from accumulated O_2 demand (the estimated O_2 demand integrated over

275   time). In accordance with Green and Dawson (1996), oxygen demand was extrapolated using

276   the equation of the $\dot{V}O_2$-power output linear regression obtained during the incremental test

277   and considering the individual value of $\dot{V}O_{2rest}$ (i.e., $\dot{V}O_2$ measured during a period of three

278   minutes before the test). The squared Bravais-Pearson correlation coefficients of linear

279   relationships between $\dot{V}O_2$ and power output ranged between 0.92 and 0.99 (mean ± SD: 0.98

280   ± 0.02). Because the present study concerned all-out exercise, O_2 demand was calculated

281   from instantaneous power output (recorded stroke by stroke) rather than mean power output

282   sustained during exercise (i.e., MPO) as initially proposed by Medbø et al. (1988).

283

284

285   *Allometric modelling procedure*

286   As LBM and age may have influenced the capacity to supply non-oxidative energy,

287   we further investigated the influence of these two factors on AOD through a multiplicative

288   allometric model proposed by Nevill and Holder (1994). This procedure considers the

289   influence of LBM and age on AOD as follows:

290

291                   $AOD = LBM^{b} \cdot \exp(a + c \cdot age) \cdot \varepsilon$ (Eq. 1)

292

293   where a is the proportionality coefficient, b and c are the scaling factors associated with LBM

294   and age, respectively, and ε is the normally disturbed error. The statistical approach to

295   allometry is to use a multiple logarithmic transformation, as previously done by Carvalho et

296   al. (2012), as follows:

297

298              $\log(AOD) = b \cdot \log(LBM) + a + c \cdot age + \log \varepsilon$ (Eq. 2)

299

300   where b and c are the slopes of the multiple linear regression. These slopes are calculated by

301   ordinary multiple regression analysis where b and c are equal to the scaling factors.

302

303   **Statistical analysis**

304   Statistical procedures were performed using Statistica 8.0 software (Statsoft, Inc.,

305   USA). Descriptive statistics were expressed as mean ± standard deviation (SD) by age group

306   (group 1: 10-11.9 yr, group 2: 12-13.9 yr, group 3: 14-15.9 yr, group 4: 16-17.9 yr) and sex,

307   as proposed by Doré et al. (2005). Data were screened for normality of distribution and

308   homogeneity of variances using a Shapiro-Wilk test and the Levene's test, respectively. Two-

309   way ANOVA was used to examine the effects of sex and age group on AOD and for

310   comparative purposes AOD in ratio with BM. When ANOVA revealed a main or interaction

311   significant effect, an HSD Tukey's *post-hoc* test was applied to test the discrimination

312   between means. The effect size and statistical power have also been reported. The effect size

313   was assessed using the partial eta-squared (η^2) and ranked as follows: ~ 0.01 = small effect,

314   ~ 0.06 = moderate effect, ≥ 0.14 = large effect (Cohen 1969). Linear regression models

315   between age, LBM, AOD, and MPO were fitted by the least-squares method by considering

316   boys and girls separately, and the squared Bravais-Pearson determination coefficients (r^2) of

317   these linear regression models were calculated. The linear regressions between age, LBM and

318   AOD were established in order to check the effects of age and LBM on AOD and then justify

319   the use of age and LBM as scaling factors through the multiplicative allometric model. The

320   slopes of relationships between AOD and MPO were compared between girls and boys using

321   an analysis of covariance (ANCOVA). This procedure was done with an adjustment on x-

322   axis (AOD) since estimation error could be greater on AOD than MPO (Brace 1977). The

323   statistical significance level was set at 5% ($p < 0.05$).

324

325   **RESULTS**

326   **Participants' physical and fitness characteristics**

327   Participants' characteristics are described by age group and sex in Table 1. Statistical

328   analysis revealed no significant sex x age group interaction effect for age [$F_{(3, 66)} = 1.29$, p =

329   0.28, $\eta^2 = 0.06$, power = 0.33]. However, there were significant sex x age group interaction

330   effects for height [$F_{(3, 66)} = 4.83$, $p < 0.01$, $\eta^2 = 0.18$, power = 0.89], BM [$F_{(3, 66)} = 6.55$, p <

331   0.001, $\eta^2 = 0.23$, power = 0.96], LBM [$F_{(3, 66)} = 9.29$, $p < 0.001$, $\eta^2 = 0.30$, power = 0.99],

332   and $\dot{V}O_{2max}$ [$F_{(3, 65)} = 8.69$, $p < 0.001$, $\eta^2 = 0.29$, power = 0.99]. No sex-related significant

333   difference was observed for height, BM, LBM and $\dot{V}O_{2max}$ before the age of 14 years.

334   However, between 14.0 and 17.9 years, boys exhibited significantly higher values for height,

335   BM, LBM and $\dot{V}O_{2max}$. Statistical analysis also revealed a significant sex effect for body fat

336   percentage [$F_{(1, 66)} = 175.5$, $p < 0.001$, $\eta^2 = 0.73$, power = 1.00]. Girls displayed significantly

337   higher values of body fat percentage than boys between 10.0 and 17.9 years ($p < 0.01$, at

338   least).

339   -   Please insert Table 1 near here –

340

341   **Determination coefficients and allometric exponents**

342   Age was positively correlated to LBM in boys ($r^2 = 0.62$, $p < 0.001$) and girls ($r^2 =$

343   0.13, $p < 0.05$). Age was also positively correlated to AOD in boys ($r^2 = 0.72$, $p < 0.001$) and

344   girls ($r^2 = 0.23$, $p < 0.01$). In addition, LBM was positively associated with AOD in boys ($r^2 =$

345   0.75, $p < 0.001$) and girls ($r^2 = 0.22$, $p < 0.01$), and with MPO in boys ($r^2 = 0.86$, $p < 0.001$)

346   and girls ($r^2 = 0.47$, $p < 0.001$).

347   Allometric scaling exponents *a*, *b*, and *c* for AOD obtained from the multiple

348   procedure (i.e., Eq. 1) were -3.99, 1.03, and 0.08 in boys. The corresponding values in girls

349   were -2.62, 0.78, and 0.04, respectively.

350

351   **Accumulated Oxygen Deficit (AOD)**

352   AOD values are displayed in absolute terms (L O_2 Eq.) and in ratio with BM (mL O_2

353   Eq.$\cdot kg^{-1}$BM) as well as with allometric exponents for LBM and age [L O_2 Eq. / (kg LBM$^b \cdot$

354    $\exp(a + c \cdot$ age))] by age group and sex in Figure 1. Regardless of sex, AOD increased with

355   age whether in absolute [$F_{(3, 66)} = 31.49$, $p < 0.001$, $\eta^2 = 0.59$, power = 1.00] or in ratio with

356   BM [$F_{(3, 66)} = 13.44$, $p < 0.001$, $\eta^2 = 0.38$, power = 0.99]. Two-way ANOVA also revealed a

357   significant sex x age group interaction effect for absolute AOD [$F_{(3, 66)} = 10.84$, $p < 0.001$, η^2

358    $= 0.33$, power = 0.99] and AOD expressed in ratio with BM [$F_{(3, 66)} = 2.79$, $p = 0.05$, $\eta^2 =$

359   0.11, power = 0.64]. *Post-hoc* tests showed significantly higher values for absolute AOD and

360   AOD in ratio with BM unit in boys than girls between 14.0 and 17.9 years ($p < 0.001$).

361   However, there was neither a significant age effect [$F_{(3, 66)} = 1.12$, $p = 0.345$, $\eta^2 = 0.05$,

362   power = 0.29] nor a sex x age group interaction effect [$F_{(3, 66)} = 0.22$, $p = 0.885$, $\eta^2 = 0.01$,

363   power = 0.08] for AOD expressed with allometric exponents (LBM and age).

364

365   -   Please insert Figure 1 near here -

366

367   **MPO and post-exercise blood responses**

368   Mean power output (MPO) and post-exercise extreme blood responses ($[La]_{max}$,

369   pH_{min}, $[HCO_3^-]_{min}$) are described by age group and sex in Table 2. Two-way ANOVA showed

370   significant sex x age group interaction effects for MPO [$F_{(3, 66)} = 13.4$, $p < 0.001$, $\eta^2 = 0.38$,

371   power = 0.99] and $[La]_{max}$ [$F_{(3, 66)} = 3.78$, $p < 0.05$, $\eta^2 = 0.15$, power = 0.79] but not for blood

372   pH_{min} [$F_{(3, 64)} = 2.0$, $p = 0.11$, $\eta^2 = 0.09$, power = 0.51] and $[HCO_3^-]_{min}$ [$F_{(3, 61)} = 0.34$, $p =$

373   0.799, $\eta^2 = 0.02$, power = 0.11]. MPO and $[La]_{max}$ significantly increased with increasing age

374   and values were significantly higher between 16.0 and 17.9 years for $[La]_{max}$ ($p < 0.001$) and

375   between 14.0 and 17.9 years for MPO ($p < 0.001$).

376

377   -   Please insert Table 2 near here -

378

379   **Relationships between AOD and MPO**

380   The relationships between AOD (L O_2 Eq.) and MPO (W) in boys and girls are

381   displayed in Figure 2. Significant positive relationships were observed between AOD and

382   MPO in boys ($r^2 = 0.89$, $p < 0.001$) and girls ($r^2 = 0.41$, $p < 0.001$). The slopes of

383   relationships between AOD and MPO were not significantly different between both sexes [F

384     $_{(1, 70)} = 2.30$, $p = 0.13$, $\eta^2 = 0.03$, power = 0.32].

385

386   -   Please insert Figure 2 near here –

387

388   **DISCUSSION**

389   The purposes of the present study were to determine during childhood and

390   adolescence (i) the effect of sex on changes in non-oxidative metabolism, as quantified by

391   AOD, and (ii) the importance of AOD on performance with respect to age and sex. The main

392   results confirm our hypotheses since boys exhibited significantly higher AOD values than

393   girls from the age of 14 years, regardless of whether AOD was expressed in absolute terms or

394   in ratio with BM. However, when AOD was analysed in relation to LBM and age in a

395   multiplicative allometric model, a significant difference was no longer observed between

396   girls and boys. In addition, AOD was positively associated with mean power output (MPO),

397   but with less evidence in girls because of a smaller change in LBM. These data show, for the

398   first time, the major role of concurrent changes in LBM and age in the sexual differentiation

399   of non-oxidative metabolism during childhood and adolescence. They also show the

400   importance of non-oxidative metabolism on performance during high-intensity whole-body

401   exercise (i.e., MPO) from childhood into adolescence, more particularly in boys. Taken

402   together, the present data provide new insights into the development and aetiology of non-

403   oxidative metabolism and performance during childhood and adolescence, especially in girls

404   who have been largely understudied compared to boys (McManus and Armstrong 2011).

405

406   The results of the present study show a significant age effect on AOD suggesting an

407   increase in non-oxidative energy production during childhood and adolescence in both sexes;

408   however, this effect was found to be less evident in girls. This study is the first to establish an

409   age effect on AOD in girls during childhood and adolescence. In the male population, some

410 studies showed a difference in AOD between prepubertal boys and young men; however,

411 these studies were not designed to test the effect of age and employed small sample numbers

412 with a lack of continuity from childhood into adolescence (Hebestreit et al. 1998; Leclair et

413 al. 2011). The results also show sex-related differences in AOD to only be present from the

414 age of 14 years. These results are consistent with previously published studies of AOD in

415 ratio with BM, which showed with small samples no sex differences in AOD between 9-11-

416 year-olds (Carlson and Naughton 1993; Naughton and Carlson 1995; Berthoin et al. 2003)

417 but significantly higher AOD values in boys than girls at 14-15 years (Naughton et al. 1997).

418

419 Sex differences in body composition exerted a strong influence on the comparison of

420 AOD between groups. Indeed, when AOD was expressed in ratio with BM, boys exhibited

421 significantly higher AOD values than girls from the age of 14 years. Multiplicative allometric

422 modelling, however, highlighted that when age is considered concurrently with LBM, the

423 difference in AOD between girls and boys decreased ($p = 0.885$) with age having a greater

424 effect on AOD in boys than girls (c: 0.08 vs. 0.04, respectively). Moreover, when age was

425 considered in the allometric procedure, AOD increased proportionally more with LBM in

426 boys ($b = 1.03$) than girls ($b = 0.78$). This is likely explained by the closer relationships

427 obtained between age, LBM and AOD in boys. Taken together, these results show that age

428 and LBM both play a major role in explaining sex-related differences in the non-oxidative

429 energy production during high-intensity exercise from the age of 14 years.

430

431 From a physiological perspective, sex-related changes in AOD from the age of 14

432 years could be attributed to hormonal factors and changes in skeletal muscle morphology due

433 to growth and specifically maturation. More explicitly, the greater increase in AOD in boys

434 could be ascribed to their higher production of androgen hormones (e.g., testosterone) at the

435   time of puberty (Korth-Schutz et al. 1976; Fahey et al. 1979). This could increase more

436   favorably muscle mass and the specific area of type II fibres and thereby the activity of non-

437   oxidative metabolism. This hypothesis is supported by some earlier studies showing

438   significant correlations between salivary or blood testosterone concentration, type II fibre

439   area (Mero 1988) and peak lactate concentration in boys (Mero 1988; Falgairette et al. 1991).

440   Oertel (1988) also showed that at least from the age of 15 years, the type II fibre area/type I

441   fibre area ratio in the vastus lateralis and deltoid muscles increases more in boys than girls. In

442   addition, although there is only one study that has compared the muscle enzyme activity

443   during growth and maturation between girls and boys, it is likely that the activity of enolase

444   (i.e., glycolytic enzyme) in the vastus lateralis is greater in boys than girls at 13-15 years of

445   age (Haralambie 1982). This sex-related difference in enzyme activity is consistent with the

446   data reported by Cumming et al. (1985) showing a higher accumulation of serum lactate after

447   maximal exercise in boys compared to girls from the age of 15 years. The results of the

448   present study confirm these data since there was a higher increase in blood lactate

449   concentration and a greater decrease in blood pH and bicarbonate concentration after the 60-s

450   all-out test in boys compared to girls from the age of 16 years. However, sex-related

451   differences were only significant for the maximal blood lactate concentration.

452

453   The results of the present study also show that AOD significantly accounted for the

454   mean power output produced during the 60-s all-out test both in girls and boys. This indicates

455   that non-oxidative metabolism could be a major determinant of performance during high-

456   intensity exercise during growth. These results are similar to those of Leclair et al. (2011)

457   which showed a significant positive correlation between AOD expressed in ratio with BM

458   and time to exhaustion during cycle exercise at 100% of maximal aerobic power in 9-11-

459   year-old boys. However, the coefficient of determination was lower in girls ($r^2 = 0.41$) than

460   boys ($r^2 = 0.89$) indicating that AOD is less important in girls in the explanation of the power

461   produced during high-intensity exercise. This may be ascribed to the fact that LBM, which is

462   the main discriminatory factor for AOD and MPO, varied much less in girls than boys (+19%

463   vs. +81%, respectively) and the lower range in LBM values in girls reduced the coefficient of

464   determination (Chen and Popovich 2002). Indirectly, this finding supports the assertion that

465   LBM has a strong influence on AOD and MPO during high-intensity exercise, but this effect

466   is more moderate in girls than boys. Finally, the slopes of relationships between AOD and

467   MPO were not significantly different between girls and boys, suggesting no difference in

468   "anaerobic delta efficiency" between both sexes. However, this finding remains to be

469   confirmed due to the high variance of AOD in girls.

470

471   **Strengths and limitations**

472   This study presents cross-sectional data and would have been enhanced with measures

473   of maturity status. However, it has been demonstrated that once age and LBM have been

474   controlled for in multiplicative allometric analyses, maturity status does not make an

475   additional, significant contribution to explaining the development of either peak aerobic or

476   peak anaerobic power of 11-18-year-olds (Armstrong and Welsman 2020a, b). The

477   estimation of LBM from BM and skinfold thicknesses rather than its direct measurement

478   using more sophisticated technology can also be criticised, but this methodology is well-

479   established in paediatric exercise physiology (Rowland et al. 1997; Janz et al. 1998;

480   Armstrong and Welsman 2020a, b). Moreover, direct measures of the body fat of children

481   and adolescents have recently been showed to vary widely across laboratory techniques

482   (Ferri-Morales et al. 2018). Finally, we can wonder about the generalization of the present

483   findings to the whole of the pediatric population since rowing is a specific activity involving

484 a larger muscle mass during exercise when compared with cycling or running, for instance

485 (Gastin 2001; Maciejewski et al. 2013).

486   A unique strength of the present study lies in the adoption for the first time of

487 allometric modelling to analyse youth AOD. This approach has provided new insights into

488 the influence of the contribution of concurrent changes in age and LBM on AOD in

489 childhood and adolescence.

490

491 **CONCLUSION**

492   The results of the present study show for the first time that energy production derived

493 from non-oxidative metabolism, quantified by AOD during high-intensity exercise, increases

494 with age with boys differing from girls from the age of about 14 years, due to their greater

495 gain in LBM. Boys exhibited significantly higher values of AOD than girls from the age of

496 14 years but multiplicative allometric modelling showed that when age is considered

497 concurrently with LBM, the sex difference in AOD is reduced during childhood and

498 adolescence. Finally, AOD was found to be a key determinant of performance during high-

499 intensity exercise during childhood and adolescence, particularly in boys owing to their

500 greater LBM gain at the time of puberty.

501

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659

Table 1. Participants' physical and fitness characteristics (n = 74).

	Group 1 (n=11) 10 – 11.9 yr		Group 2 (n=17) 12 – 13.9 yr		Group 3 (n=27) 14 – 15.9 yr		Group 4 (n=19) 16 – 17.9 yr	
	Girls (n=6)	*Boys (n=5)*	*Girls (n=6)*	*Boys (n=11)*	*Girls (n=15)*	*Boys (n=12)*	*Girls (n=8)*	*Boys (n=11)*
Age (yr)	11.0±0.7	11.5±0.3	12.6±0.7	13.2±0.3	14.8±0.4	14.9±0.6	16.0±0.8	16.9±0.5
Height (m)	1.55±0.05	1.51±0.13	1.63±0.08	1.64±0.08	1.66±0.04	1.79±0.07 [**]	1.65±0.05	1.78±0.07 [**]
BM (kg)	48.6±4.8	41.1±8.8	58.8±11.7	53.6±8.7	58.4±6.2	65.6±9.4	56.7±4.5	70.0±5.7 [**]
Body fat (%)	24.9±6.1	15.7±1.7 [**]	25.2±5.0	12.9±5.6 [***]	21.8±3.5	6.5±1.9 [***]	23.1±1.8	10.4±2.0 [***]
LBM (kg)	36.3±2.7	34.5±6.9	43.6±7.0	46.7±8.6	45.5±4.5	61.3±8.8 [***]	43.5±3.7	62.6±4.9 [***]
$\dot{V}O_{2max}$ (L·min^{-1})	1.99±0.2	2.30±0.5	2.32±0.2	2.90±0.7	2.63±0.3	4.14±0.5 [***]	2.89±0.3	4.53±0.3 [***]

Values are presented as mean ± SD. BM: body mass; LBM: lean body mass; $\dot{V}O_{2max}$: maximal oxygen uptake. [**], and [***]: significantly different from girls within each age group at $p < 0.01$ and $p < 0.001$, respectively.

Table 2. Mean power output and post-exercise extreme blood responses obtained after a 60-s all-out test in girls (n = 35) and boys (n = 39).

	Group 1 (n=11) 10 – 11.9 yr		Group 2 (n=17) 12 – 13.9 yr		Group 3 (n=27) 14 – 15.9 yr		Group 4 (n=19) 16 – 17.9 yr	
	Girls (n=6)	*Boys (n=5)*	*Girls (n=6)*	*Boys (n=11)*	*Girls (n=15)*	*Boys (n=12)*	*Girls (n=8)*	*Boys (n=11)*
MPO (W)	153±16	178±45	219±40	276±71 [†]	261±33 [††]	440±76 [†††, ***]	283±43 [†††]	520±55 [†††, ***]
[La]$_{max}$ (mmol·L^{-1})	8.2±1.0	9.3±1.4	10.5±0.7	11.4±0.8	12.3±2.0 [†††]	14.1±1.5 [†††]	12.3±1.8 [†††]	16.4±1.9 [†††, **]
pH$_{min}$	7.27±0.02	7.27±0.03	7.21±0.05	7.22±0.02	7.20±0.05	7.17±0.05	7.19±0.04	7.12±0.05
[HCO$_3^-$]$_{min}$ (mmol·L^{-1})	15.9±1.0	14.3±1.6	12.4±1.4	11.0±2.3	12.1±2.2	9.6±2.1	11.4±1.7	9.7±1.5

MPO: mean power output; [La]$_{max}$: maximal blood lactate concentration; pH$_{min}$: minimal blood pH; [HCO$_3^-$]$_{min}$: minimal blood bicarbonate ions concentration. Values are presented as mean ± SD. [†], [††], [†††]: significantly different from the group 1 within each sex category at $p < 0.05$, $p < 0.01$, and $p < 0.001$. [*], [**], and [***]: significantly different from girls within each age group at $p < 0.05$, $p < 0.01$, and $p < 0.001$ respectively.

FIGURE LEGENDS

Figure 1. AOD expressed in absolute values (Panel A), in ratio with BM (Panel B), and with allometric exponents (Panel C) by age group and sex (girls in white bars and boys in black bars).

Figure 2. Relationships between AOD (L O_2 Eq.) and MPO (W) in girls (white circles and dash line) and boys (black circles and full line). The 95% confidence intervals are shown in gray. The regressions obtained between AOD and MPO were adjusted on x-axis (AOD) since estimation error could be greater on AOD than MPO.
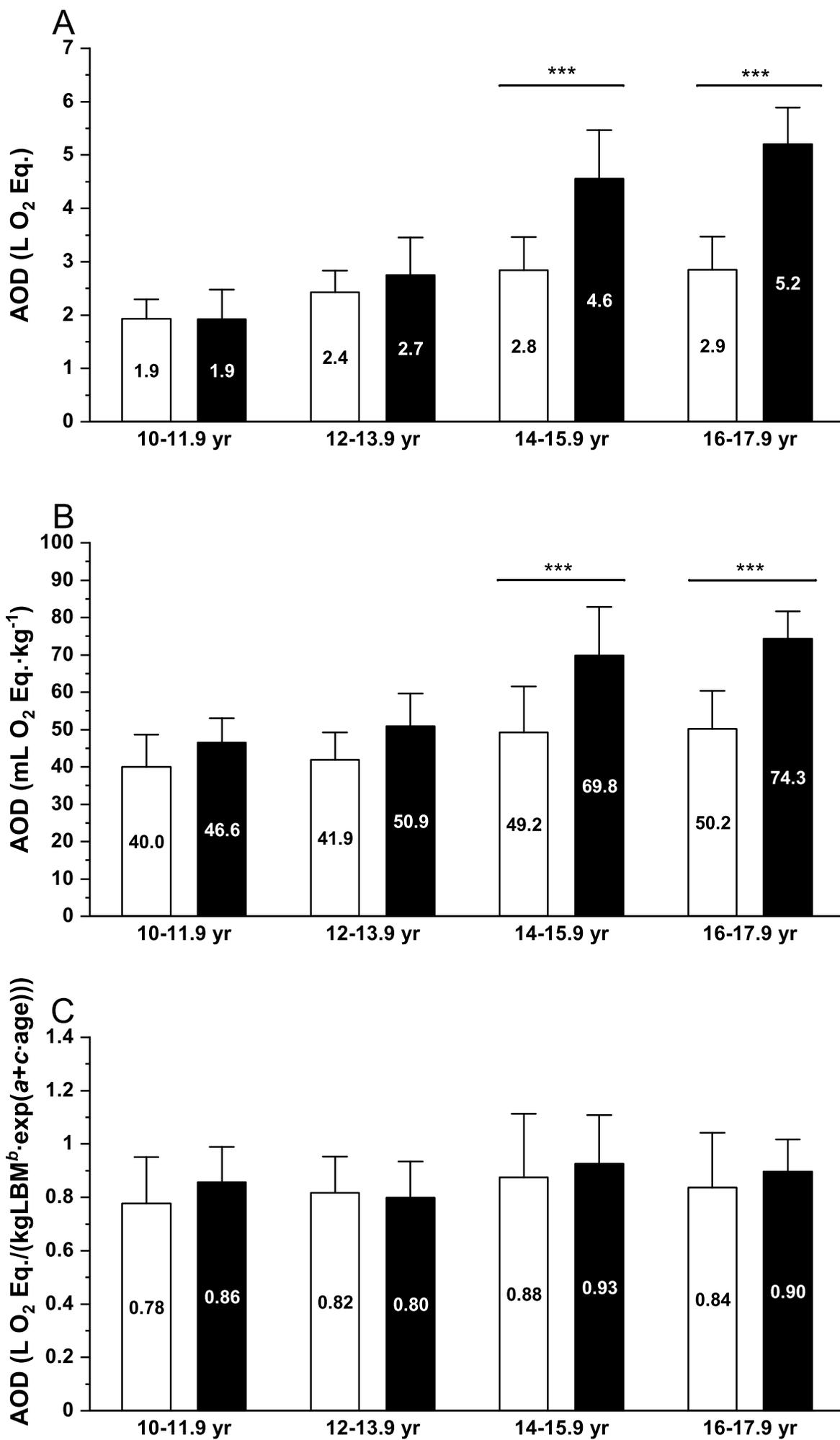
Figure 1

Figure 2

Boys n = 39, r^2 = 0.89, p < 0.001
Girls n = 35, r^2 = 0.42, p < 0.001