

1 **TITLE PAGE**

2 **Title:** Iron and vitamin status biomarkers and its association with physical fitness in
3 adolescents. The HELENA study.

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40

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49 **Running head:** Micronutrient biomarkers and fitness in adolescents

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60 **ABSTRACT**

61 There is a lack of studies that analyse the association between micronutrient-related
62 biomarker status and physical fitness in adolescents. In the present study, biochemical
63 parameters for iron and vitamin status were studied along with objective measures of
64 physical fitness in healthy male and female European adolescents. 1089 adolescents (580
65 girls, 12.5-17.5 years) from the HELENA cross-sectional study were included. Hierarchical
66 linear models were performed to determine the associations between micronutrient
67 biomarkers and physical fitness. Age, seasonality, latitude, body mass index, menarche (in
68 girls) and physical activity were used as covariates. For cardiorespiratory fitness,
69 concentrations of hemoglobin, retinol and vitamin C in male adolescents and, β -carotene and
70 25(OH)D in female adolescents were associated with VO_{2max} . For muscular fitness,
71 concentrations of hemoglobin, β -carotene, retinol and α -tocopherol in male adolescents and
72 β -carotene and 25(OH)D in female adolescents were associated with better performance of
73 the standing long jump test. In summary, concentrations of hemoglobin and most antioxidant
74 vitamins in male adolescents and β -carotene and 25(OH)D in female adolescents were
75 positively associated with cardiorespiratory and muscular fitness, after controlling for
76 relevant confounders. The associations between physical fitness and iron or vitamin status
77 observed in this cross-sectional study in adolescents should be followed up by a study
78 specifically designed to evaluate causal relationships.

79

80 **Keywords:** iron status, vitamins, 25-hydroxyvitamin D, physical performance, adolescence.

81 INTRODUCTION

82 Adolescence is a critical period of growth, development and for the acquisition of healthy
83 behaviors (31). Appropriate nutrition during this period is a basic requirement to express
84 genetic potential that together with physical activity (PA) will influence later adult and
85 elderly health outcomes. Physical fitness is a set of attributes related to a person's ability to
86 perform physical activities that require aerobic capacity, endurance, strength or flexibility
87 and is mainly determined by a combination of regular PA and genetically inherited ability
88 (9). Physical fitness is frequently evaluated in adolescents and it is known to be a powerful
89 marker for present (youth) and future (adult) health (39). Scientific evidence shows that the
90 adolescents' performance in these tests has declined in the last three decades (49, 50). For
91 some micronutrients an at least marginally deficient nutritional status has been also
92 identified (3, 52). It has been stated in the literature that physical fitness interacts with the
93 nutritional status of the individuals (29), which at the same time can differ according to
94 gender, age, latitude, ethnicity, climate, seasonality, genetic background, adiposity and
95 lifestyle factors (4, 8, 16, 23, 41, 47, 51).

96 It is known that hemoglobin is the oxygen carrier to the muscles. Some studies have shown
97 that iron status is associated with physical fitness, mainly in its cardiorespiratory dimension
98 (54). Some vitamins, such as vitamin C, have biological effects which are associated with
99 sports performance and recovery from intense training, such as antioxidant function,
100 immunocompetence, collagen metabolism and carnitine biosynthesis (29). 25-
101 hydroxyvitamin D [(25(OH)D] has been shown to affect skeletal muscle strength and
102 function, acting on calcium mechanisms, cell proliferation and differentiation, preventing
103 against insulin resistance and arachidonic acid mobilization, and other mechanisms (7, 15),
104 being also related to fitness performance (16, 21). Nevertheless, the association between
105 status of some micronutrients and physical performance remain still controversial. In

106 addition, limited information is available concerning this association in the adolescent
107 population, taking into account the important effect of the above-mentioned confounders.
108 In this study, we hypothesized that iron and vitamin status status is directly associated with
109 cardiorespiratory (CRF) and muscular fitness in adolescents.

110

111 **MATERIAL AND METHODS**

112 *Study design*

113 The HELENA-CSS is a European Union-funded project conducted on adolescents from 10
114 European cities: Stockholm (Sweden), Athens and Heraklion (Greece), Rome (Italy),
115 Zaragoza (Spain), Pecs (Hungary), Ghent (Belgium), Lille (France), Dortmund (Germany)
116 and Vienna (Austria) (33). Detailed descriptions of the HELENA sampling and recruitment
117 approaches, standardization and harmonization processes, data collection, analysis
118 strategies, quality control activities and inclusion criteria have been described in detail
119 elsewhere (32). An extended and detailed manual of operations was designed for and
120 thoroughly read by every researcher involved in the field work before the data collection
121 started. Parents and adolescents signed an informed consent, the protocol was approved by
122 Research Ethics Committees of each city involved and the study has been performed
123 following the ethical guidelines of the Declaration of Helsinki 1964 (revision of Edinburgh
124 2000), Convention of Oviedo (1997), the Good Clinical Practice, and the legislation about
125 clinical research in humans in each of the participating countries.

126

127 *Study sample*

128 The geographical distribution of the 10 cities (>100,000 inhabitants) was not random and
129 not represented by the strata, but it was decided according to the following criteria:
130 representation of territorial units (countries) of Europe according to geographical location

131 (North/South/East/West), cultural reference and socioeconomic situation; and selection of a
132 territorial unit (city) in the country, which had an experienced research group to perform the
133 study. The age range considered valid for the HELENA study was 12.5-17.5 y. All the
134 analyses conducted on the HELENA data are adjusted by a weighing factor to balance the
135 sample according to the theoretical age distribution foreseen. A total of 3528 adolescents,
136 1683 males and 1845 females, were considered eligible for the HELENA analyses.
137 In the HELENA-CSS protocol, it was established that blood samples were obtained
138 randomly in one third of the population sample. Therefore, a total of 1089 adolescents (509
139 males and 580 females) were included in this report. To make maximum use of the data, all
140 valid data on physical fitness components were included in this report. Consequently,
141 sample sizes vary for the different physical fitness tests and biomarkers.

142

143 *Anthropometric measurements*

144 International guidelines for anthropometry in adolescents were used in the HELENA study
145 (35). Barefoot and in light indoor clothing, body weight (Kg) and height (cm) were
146 measured with an electronic scale (Type SECA 861), precision 100 g, range 0 – 150 Kg and
147 a stadiometer (Type Seca 225), precision 0,1 cm, range 70 – 200 cm, respectively. Body
148 mass index (BMI) was calculated as body weight (Kg) divided by height (m) squared.

149

150 *Physical fitness tests*

151 The physical fitness components, *i.e.* muscular fitness and aerobic capacity, were assessed
152 by the physical fitness tests previously described in detail (37). The scientific rationale for
153 the selection of all of these tests, as well as their reliability in young people, was previously
154 published (38). Lower-body muscular strength was assessed with the *standing long jump* test
155 (SLJ), which has shown to be a good indicator of overall muscular fitness in youth (10).

156 This test was performed twice and the best score was retained. CRF was assessed with the
157 *20m shuttle run* test (stage). A stage is the period of time in which the speed maintains
158 constant. In this test, the initial speed is $8.5\text{km}\cdot\text{h}^{-1}$, which is increased by $0.5\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$ (1
159 min equals one stage) (24). Léger equation was used to estimate the maximal oxygen
160 consumption ($\text{VO}_{2\text{max}}$) from 20m shuttle run test (28). This test was performed only once.

161

162 *Specimen collection and biochemical analyses*

163 The blood sampling procedure and sample logistics have been described in detail elsewhere
164 (22). Briefly, fasting blood samples (24.3 ml) were collected by venipuncture at school
165 between 8 and 10 o'clock in the morning after a 10-hour overnight fast. Samples for the
166 different analyses were manipulated *in situ* as described below and transported according to
167 the protocol to the central laboratory in Bonn, Department of Nutrition and Food Sciences,
168 for further manipulation. Whole-blood samples for the red blood parameters, including
169 hemoglobin, were sent directly to the local laboratory of each country to be analysed.

170 A specific handling, transport and traceability system for biological samples was developed
171 for the HELENA study and was already described by González-Gross et al. (22). Blood
172 samples were obtained between October 2006 and June 2007 and in October 2007. Blood
173 sampling date was dependent from local field work planning, agreement of the school and
174 availability and capacity of the central laboratory.

175

176 *Iron status assessment*

177 Blood sampling procedure and laboratory measures for iron status indicators [sTfR and
178 serum ferritin] have been described elsewhere (20, 22). Briefly, sTfR and serum ferritin
179 were measured using ELISA (enzyme-linked immunosorbent assay) (19) in the Human
180 Nutrition Laboratory of the National Research Institute on Food and Nutrition (Rome, Italy).

181 A commercially available control sample from Bio-Rad Liquichek Immunology Control
182 Level 3 (Bio-Rad, Milan, Italy) was used to obtain a calibration curve on each plate.

183

184 *Provitamin A (β -carotene), vitamin A (retinol) and vitamin E (α -tocopherol) measurements*

185 β -carotene, retinol and α -tocopherol were analysed by reversed phase high-performance
186 liquid chromatography using UV detection (RP-HPLC) (Sykam Gilching Germany) in
187 serum. The vacutainer was centrifuged for 15 min at 3,500 r.p.m. at 4°C. Standards (β -
188 carotene, retinol, α -tocopherol), hexane and isopropanol were obtained from Sigma Aldrich
189 (Germany) and had all HPLC-grade. The variation of the method is below 3% for all the
190 vitamins. The samples were stable over 24 hours at room temperature (coefficient of
191 variation (CV) vitamin E = 4.6%; vitamin A = 3.2%).

192

193 *Vitamin C measurement*

194 For vitamin C measurements the heparin tubes were put immediately on ice and centrifuged
195 within 30 min (3,500 r.p.m. for 15 min.). For stabilization, heparin plasma was precipitated
196 with a 6% (w/w) perchloric acid solution spiked with metaphosphoric acid (1:1). The
197 precipitated samples were transported at a stable temperature of 4-7°C within 24h to the
198 central laboratory and stored at -80°C until analysis. Plasma Vitamin C was analysed by RP-
199 HPLC using UV-detection (Sykam Gilching Germany). The CV of the Method was 1.7%.

200

201 *Vitamin B₆, B₁₂ (cobalamin and holo-transcobalamin) and folate (plasma and red blood
202 cell) measurements*

203 For the measurement of vitamin B₆ (pyridoxal 5'-phosphate), aliquots of EDTA whole blood
204 were sent by cooled transport to the central laboratory and stored at -80°C until bunched
205 analysis. Pyridoxal 5'-phosphate was measured by HPLC (Varian Deutschland GmbH,

206 Darmstadt, Germany; CV = 1%) with a modified method of Kimura et al. (26). For vitamin
207 B₁₂ status, cobalamin and holo-transcobalamin were determined. For folate status, plasma
208 folate and red blood cell (RBC) folate were determined. For the measurement of cobalamin
209 and plasma folate, blood was collected in heparinized tubes, immediately placed on ice, and
210 centrifuged within 30 min (3500 rpm for 15 min). The supernatant fluid was transported at a
211 stable temperature of 4-7°C to the central laboratory and stored there at -80°C until assayed.
212 After measuring the hematocrit in situ, EDTA whole blood was sent to the central laboratory
213 for the RBC folate analysis. EDTA whole blood was diluted 1:5 with freshly prepared 0.1%
214 ascorbic acid for cell lysis incubated for 60 min in the dark before storage at -80°C.
215 Cobalamin, plasma and RBC folate were measured by competitive immunoassay (Immulite
216 2000, DPC Biermann GmbH, Bad Nauheim, Germany); (CV for plasma folate = 5.4%, RBC
217 folate = 10.7%, Cobalamin = 5.0%). Sera for measuring holo-transcobalamin were obtained
218 by centrifuging blood collected in evacuated tubes without anticoagulant at 3,500 r.p.m for
219 15 min within one hour. Once sent to the central laboratory, the sera were aliquoted and
220 stored at -80°C until transport in dry ice to the biochemical lab at the Universidad
221 Politécnica de Madrid for analysis (Laboratorio número 242 de la Red de Laboratorios de la
222 Comunidad de Madrid). Holo-transcobalamin was measured by microparticle enzyme
223 immunoassay (Active B₁₂ Axis-Shield Ltd, Dundee, Scotland, UK; CV = 5.1%) with the use
224 of AxSym (Abbot Diagnostics, Abbott Park, IL, USA).

225

226 *25(OH)D measurement*

227 For vitamin D status, plasma 25(OH)D was measured. Blood was collected in EDTA tubes
228 transported at room temperature to the central laboratory at IEL within 24 h. There it was
229 centrifuged at 3,500 rpm for 15 min at 4°C and the supernatant stored at -80°C till analysis.

230 Plasma 25(OH)D was analysed by ELISA using a kit (OCTEIA 25-Hydroxy Vitamin D)
231 from Immunodiagnostic System (Germany) and measured with a Sunrise™ Photometer by
232 TECAN (Germany). The IDS OCTEIA 25(OH)D kit is an enzyme immunoassay intended
233 for the quantitative determination of 25(OH)D and other hydroxylated metabolites in human
234 serum or plasma. The sensitivity of this method is 5 nmol/L 25(OH)D and the variation is
235 below 6 %. The mean recovery of 25(OH)D is 101%. The coefficient of variation for the
236 method was below 1%.

237

238 *Seasonality*

239 A variable was computed by re-coding the original variable “Blood drawing date” into
240 “Seasonality”, as follows: winter (from 21st December to 20st March, coded as 1), autumn
241 (from 21st September to 20th December, coded as 2), spring (from 21st March to 20th June,
242 coded as 3) and summer (from 21st June to 20th September, coded as 4), as it was performed
243 in previous studies (16). As the HELENA study was performed during the academic year,
244 few adolescents (N=25) were assessed in the first days of summer, and they were included
245 along with those assessed during spring. Therefore, the final variable was composed by 3
246 groups: winter (coded as 1), autumn (coded as 2) and spring (coded as 3).

247

248 *Latitude of residence*

249 The latitude of the study centers was also taken into account as a confounder in the analyses.
250 The latitude of each city was obtained from <http://maps.google.es/>. Latitudes of the involved
251 cities were: Stockholm (59°33′ N), Dortmund (51°51′ N), Ghent (51°06′ N), Lille (50°63′
252 N), Vienna (48°21′ N), Pecs (46°07′ N), Rome (41°89′ N), Zaragoza (41°66′ N), Athens
253 (37°98′ N) and Heraklion (35°33′ N). To make use of this data, latitudes were added to the
254 database as numeric variables with two decimals (i.e. Stockholm = 59.55).

255

256 *Age at menarche*

257 A quantitative variable was computed as a measure of time (months) as follows: menarche
258 (months) = age (months) at the moment of blood drawing – age (months) at the moment of
259 menarche. Those girls (n=104) who had no menarche before blood drawing were considered
260 as “0” for the analyses.

261

262 *Physical activity assessment*

263 A uni-axial accelerometer (Actigraph GT1M, Manufacturing Technology Inc. Pensacola,
264 FL, USA) was used to assess physical activity (PA) as described previously (44). In this
265 study, the interval of time (epoch) was set at 15 seconds. The time spent (minutes/day) at
266 moderate PA (MPA) [4-6 metabolic equivalents (METs)] was calculated based upon a cut-
267 off of 2000-3999 counts per minute (cpm). The time spent (minutes/day) at vigorous PA (>6
268 METs) was calculated based upon a cut-off of 4000 cpm. Further, moderate to vigorous PA
269 (MVPA) (>4 METs) was calculated as the sum of moderate and vigorous PA. The cut-offs
270 to define the intensity categories are similar to those used in previous studies (17).
271 Subjects were classified as non-active adolescents (<60 minutes/day of MVPA) and active
272 adolescents (\geq 60 minutes/day of MVPA) according to the recent guidelines launched by the
273 U.S. Department of Health and Human Services and other medical institutions (1).

274

275 *Statistical methods*

276 After square root transformation of serum ferritin and natural logarithm transformation of
277 sTfR, β -carotene, retinol, vitamin B₆, cobalamin, holo-transcobalamin, plasma folate and
278 RBC folate, all the residuals showed a satisfactory pattern (normal distribution). Since
279 interactions between sex and the studied variables were observed ($p < 0.001$), results are

280 given separately by gender. Descriptive data were assessed by one-way analysis of variance
281 (ANOVA) for normally distributed variables and by *U* Mann Whitney for non-normally
282 distributed variables.

283 The relationships among micronutrient biomarkers, i.e. iron, hydrosoluble and liposoluble
284 vitamins and the performance in the physical fitness tests, i.e. 20m shuttle run and SLJ, were
285 assessed using hierarchical linear models. The adjusted analysis was conducted according to
286 a previously formulated hierarchical model, including different models: 1) age, seasonality
287 and latitude 2) nutritional status and menarche (in females) 3) MVPA and 4-7) micronutrient
288 biomarkers. At each model of micronutrient biomarkers, the variables were controlled for
289 those at the same level and the levels above (models 1-3) (53). For a variable to remain in
290 the model, a significance level of $P < 0.20$ was required.

291 All the analyses were performed using the Statistical Package for Social Sciences software
292 (SPSS, v. 15.0 for WINDOWS; SPSS Inc., Chicago, IL, USA), and values of $p < 0.05$ were
293 considered statistically significant. Figures were performed using Sigmaplot (v. 10.0 for
294 WINDOWS; Systat Software Inc., San José, California).

295

296 **RESULTS**

297 Table 1 shows descriptive characteristics of the sample by sex.

298 **Micronutrient status and CRF in adolescents**

299 Results from the hierarchical linear models investigating the relationship between the
300 adolescent CRF (assessed by VO_{2max}), and their micronutrient-related biomarker status are
301 presented in tables 2 and 3. In male adolescents, adjusted results showed that hemoglobin
302 ($\beta = 0.192$), retinol and vitamin C ($\beta = 0.148$ and $\beta = 0.186$, respectively) were associated with
303 VO_{2max} (table 2). In female adolescents, adjusted results showed that β -carotene ($\beta = 0.101$)
304 and 25(OH)D ($\beta = 0.091$) were associated with VO_{2max} (table 3).

305

306 Micronutrients and muscular fitness in adolescents

307 Results from the hierarchical linear models investigating the relationship between the
308 adolescent muscular fitness (assessed by SLJ), and their micronutrient-related biomarker
309 status are presented in tables 4 and 5. In male adolescents, adjusted results showed that
310 hemoglobin ($\beta= 0.203$), β -carotene ($\beta= 0.160$), retinol ($\beta= 0.128$) and α -tocopherol ($\beta= -$
311 0.135) were associated with SLJ (table 4). In female adolescents, adjusted results showed
312 that β -carotene ($\beta= 0.177$) and 25(OH)D ($\beta= 0.125$) were associated with SLJ (table 5).

313

314 DISCUSSION

315 In the present study we examined cross-sectional associations of micronutrient-related
316 biomarker status with the performance in physical fitness tests in a large sample of European
317 adolescents from ten cities. The studied cities were equivalent and comparable among
318 countries but the samples were representative for the cities and not for the countries (32). To
319 the best of our knowledge, there is limited literature concerning the association among
320 micronutrient status and physical fitness in adolescents.

321 In our study, hemoglobin concentration was positively associated with CRF (assessed
322 through VO_{2max}) in male adolescents after controlling for relevant confounders. The
323 influence of iron status (i.e. hemoglobin) on physical fitness has been studied and
324 demonstrated during decades (12, 36). A recent study showed that severe iron deficiency
325 (males, <0.75 mg/L and females, <0.73 mg/L) impaired aerobic capacity, assessed through
326 VO_{2max} (54). Our finding of a positive association between blood hemoglobin and muscular
327 fitness (assessed through SLJ) in male adolescents is novel, but previous studies found
328 positive associations between serum ferritin and the performance in SLJ in males (5),

329 enhancing the importance of iron status not only in relation to CRF but also muscular
330 fitness.

331 The concentrations of antioxidant vitamins in adolescents participating in the HELENA
332 study were recently described and published (8). In our study, we found that concentrations
333 of retinol and vitamin C in male adolescents and β -carotene in female adolescents were
334 positively associated with CRF, after controlling for relevant confounders. Our results agree
335 with those shown in the study of Suboticanec-Buzina et al. (48) who reported that vitamin C
336 supplementation resulted in a significant increase in CRF (VO_{2max}) in adolescents with
337 initially lower values. In contrast, studies performed in young adults showed that vitamin C
338 was not associated with CRF (13, 56). Therefore, there is no a clear evidence of a benefit of
339 vitamin C supplementation on physical performance, suggesting further research. However,
340 vitamin C may exert permissive effects on physiologic functions, such as antioxidant,
341 immunocompetence and collagen repair, which are associated with recovery from intense
342 training, and as consequence, promoting performance (29). Our results support the positive
343 correlations found in female adolescents between β -carotene concentrations and CRF
344 (VO_{2max}) in the study of Lloyd et al. (30); however, a later review showed that any positive
345 effects of β -carotene on performance remains to be determined (29). Regarding muscular
346 fitness (SLJ), we found positive associations with β -carotene (in both sexes) and retinol in
347 male adolescents, after controlling for relevant confounders. In addition, α -tocopherol was
348 negatively associated with muscular fitness (SLJ) in male adolescents. Some studies showed
349 that the performance in standard exercise tests (45), CRF (VO_{2max}) (45), muscular fitness
350 (handgrip test) (46), swimming endurance (27, 45), or blood lactate concentrations (27) was
351 not affected by long-term α -tocopherol supplementation. . However, there are no studies
352 analyzing the relationship between α -tocopherol and the lower limbs strength and therefore,
353 the physiological factors behind cannot be elucidated, suggesting the need of more studies.

354 In recent years, vitamin D has been the most widely studied micronutrient in relation with
355 physical fitness. The concentrations of 25(OH)D in adolescents participating in the
356 HELENA study were recently described and published (23). In our study, we found positive
357 associations between 25(OH)D, cardiorespiratory and muscular fitness only in female
358 adolescents, after controlling for relevant confounders. Our results support previous
359 evidence that shows a positive association between circulating 25(OH)D and CRF (VO_{2max})
360 (16, 34, 42). In addition, our results support previous studies that showed positive
361 associations between 25(OH)D and muscular fitness (assessed through handgrip test and/or
362 pliometric tests) in females (21, 42, 55). It has been shown that vitamin D affects skeletal
363 muscle strength and function, acting on calcium mechanisms, cell proliferation and
364 differentiation, preventing against insulin resistance and arachidonic acid mobilization, or
365 other mechanisms (7, 15). However, with this study it is not possible to disentangle the
366 mechanisms by which 25(OH)D affects cardiovascular and muscle function in our
367 population.

368

369 *Limitations and strengths*

370 Although we controlled for several potential confounders, we cannot be certain that other
371 unmeasured confounders have not influenced our observations. Cross-sectional studies
372 provide evidence of associations. However, in this specific case, it seems reasonable to think
373 that micronutrient status can influence physical fitness, whereas it is not so clear the
374 mechanisms by which physical fitness could determine higher or lower micronutrient status.
375 It should also be considered that sexual maturation was not included as a covariate in our
376 analyses, due to it was not available on the whole sample. However, the age of the
377 adolescents was used instead, which showed a slight and stronger association with the
378 dependent variables.

379 Despite the aforementioned, this is the first study reporting the association between different
380 physical fitness components (i.e. CRF and muscular fitness) and a large number of
381 micronutrient biomarkers in a large sample of European adolescents. The fitness tests used
382 in the present report showed a good criterion-related validity in adolescents (43). In addition,
383 this study includes important sets of confounders, i.e. age, seasonality, latitude, BMI,
384 menarche (in females) and MVPA, which is crucial to analyse the association among
385 micronutrient-related biomarker status and physical fitness.

386 In summary, concentrations of hemoglobin and most antioxidant vitamins in males and β -
387 carotene and 25(OH)D in females were positively associated with cardiorespiratory and
388 muscular fitness in a large sample of European adolescents, after controlling for relevant
389 confounders. The associations between physical fitness and iron or vitamin status observed
390 in this cross-sectional study in adolescents should be followed up by a study specifically
391 designed to evaluate causal relationships.

392

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414 REFERENCES

- 415 1. U.S. Department of Health and Human Services. Key Guidelines for Children and
416 Adolescents [September, 2011].
- 417 2. **Agarwal M, Phan A, Willix R, Jr., Barber M, and Schwarz ER.** Is vitamin D
418 deficiency associated with heart failure? A review of current evidence. *J Cardiovasc*
419 *Pharmacol Ther* 16: 354-363, 2011.
- 420 3. **Al-Tahan J, Gonzalez-Gross M, and Pietrzik K.** B-vitamin status and intake in
421 European adolescents. A review of the literature. *Nutr Hosp* 21: 452-465, 2006.
- 422 4. **Arguelles LM, Langman CB, Ariza AJ, Ali FN, Dilley K, Price H, Liu X, Zhang**
423 **S, Hong X, Wang B, Xing H, Li Z, Liu X, Zhang W, Xu X, and Wang X.** Heritability
424 and environmental factors affecting vitamin D status in rural Chinese adolescent twins. *J*
425 *Clin Endocrinol Metab* 94: 3273-3281, 2009.
- 426 5. **Arsenault JE, Mora-Plazas M, Forero Y, Lopez-Arana S, Jauregui G, Baylin A,**
427 **Gordon PM, and Villamor E.** Micronutrient and anthropometric status indicators are
428 associated with physical fitness in Colombian schoolchildren. *Br J Nutr* 1-12, 2011 doi:
429 10.1017/S00071145100005647.
- 430 6. **Bartoszewska M, Kamboj M, and Patel DR.** Vitamin D, muscle function, and
431 exercise performance. *Pediatr Clin North Am* 57: 849-861, 2010.
- 432 7. **Boland RL.** VDR activation of intracellular signaling pathways in skeletal muscle.
433 *Mol Cell Endocrinol* 347: 11-16, 2011.
- 434 8. **Breidenassel C, Valtuena J, Gonzalez-Gross M, Benser J, Spinneker A, Moreno**
435 **LA, de Henauw S, Widhalm K, Molnar D, Maiani G, and Stehle P.** Antioxidant vitamin
436 status (A, E, C, and beta-carotene) in European adolescents - the HELENA Study. *Int J*
437 *Vitam Nutr Res* 81: 245-255, 2011.
- 438 9. **Caspersen CJ, Powell KE, and Christenson GM.** Physical activity, exercise, and
439 physical fitness: definitions and distinctions for health-related research. *Public Health Rep*
440 100: 126-131, 1985.
- 441 10. **Castro-Pinero J, Ortega FB, Artero EG, Girela-Rejon MJ, Mora J, Sjostrom M,**
442 **and Ruiz JR.** Assessing muscular strength in youth: usefulness of standing long jump as a
443 general index of muscular fitness. *J Strength Cond Res* 24: 1810-1817, 2010.
- 444 11. **Ceglia L.** Vitamin D and its role in skeletal muscle. *Curr Opin Clin Nutr Metab*
445 *Care* 12: 628-633, 2009.
- 446 12. **Cullumbine H.** Hemoglobin concentration and physical fitness. *J Appl Physiol* 2:
447 274-277, 1949.
- 448 13. **Chawla K, Mishra R, Sachdeva V, and Beenu.** Correlation of antioxidants and
449 fitness levels in undergraduate medical students. *Indian J Physiol Pharmacol* 51: 293-295,
450 2007.
- 451 14. **Chen S, Law CS, Grigsby CL, Olsen K, Hong TT, Zhang Y, Yeghiazarians Y,**
452 **and Gardner DG.** Cardiomyocyte-specific deletion of the vitamin D receptor gene results
453 in cardiac hypertrophy. *Circulation* 124: 1838-1847, 2011.
- 454 15. **Dirks-Naylor AJ, and Lennon-Edwards S.** The effects of vitamin D on skeletal
455 muscle function and cellular signaling. *J Steroid Biochem Mol Biol* 125: 159-168, 2011.
- 456 16. **Dong Y, Pollock N, Stallmann-Jorgensen IS, Gutin B, Lan L, Chen TC, Keeton**
457 **D, Petty K, Holick MF, and Zhu H.** Low 25-hydroxyvitamin D levels in adolescents: race,
458 season, adiposity, physical activity, and fitness. *Pediatrics* 125: 1104-1111, 2010.
- 459 17. **Ekelund U, Anderssen SA, Froberg K, Sardinha LB, Andersen LB, and Brage**
460 **S.** Independent associations of physical activity and cardiorespiratory fitness with metabolic
461 risk factors in children: the European youth heart study. *Diabetologia* 50: 1832-1840, 2007.

- 462 18. **El-Hajj Fuleihan G, Nabulsi M, Tamim H, Maalouf J, Salamoun M, Khalife H,**
 463 **Choucair M, Arabi A, and Vieth R.** Effect of vitamin D replacement on musculoskeletal
 464 parameters in school children: a randomized controlled trial. *J Clin Endocrinol Metab* 91:
 465 405-412, 2006.
- 466 19. **Erhardt JG, Estes JE, Pfeiffer CM, Biesalski HK, and Craft NE.** Combined
 467 measurement of ferritin, soluble transferrin receptor, retinol binding protein, and C-reactive
 468 protein by an inexpensive, sensitive, and simple sandwich enzyme-linked immunosorbent
 469 assay technique. *J Nutr* 134: 3127-3132, 2004.
- 470 20. **Ferrari M, Mistura L, Patterson E, Sjostrom M, Diaz LE, Stehle P, Gonzalez-**
 471 **Gross M, Kersting M, Widhalm K, Molnar D, Gottrand F, De Henauw S, Manios Y,**
 472 **Kafatos A, Moreno LA, and Leclercq C.** Evaluation of iron status in European adolescents
 473 through biochemical iron indicators: the HELENA Study. *Eur J Clin Nutr* 65: 340-349,
 474 2011.
- 475 21. **Foo LH, Zhang Q, Zhu K, Ma G, Hu X, Greenfield H, and Fraser DR.** Low
 476 vitamin D status has an adverse influence on bone mass, bone turnover, and muscle strength
 477 in Chinese adolescent girls. *J Nutr* 139: 1002-1007, 2009.
- 478 22. **Gonzalez-Gross M, Breidenassel C, Gomez-Martinez S, Ferrari M, Beghin L,**
 479 **Spinneker A, Diaz LE, Maiani G, Demailly A, Al-Tahan J, Albers U, Warnberg J,**
 480 **Stoffel-Wagner B, Jimenez-Pavon D, Libersa C, Pietrzik K, Marcos A, and Stehle P.**
 481 Sampling and processing of fresh blood samples within a European multicenter nutritional
 482 study: evaluation of biomarker stability during transport and storage. *Int J Obes (Lond)* 32
 483 Suppl 5: S66-75, 2008.
- 484 23. **Gonzalez-Gross M, Valtuena J, Breidenassel C, Moreno LA, Ferrari M,**
 485 **Kersting M, De Henauw S, Gottrand F, Azzini E, Widhalm K, Kafatos A, Manios Y,**
 486 **and Stehle P.** Vitamin D status among adolescents in Europe: the Healthy Lifestyle in
 487 Europe by Nutrition in Adolescence study. *Br J Nutr* 107: 755-764, 2012.
- 488 24. **Gracia-Marco L, Vicente-Rodriguez G, Casajus JA, Molnar D, Castillo MJ, and**
 489 **Moreno LA.** Effect of fitness and physical activity on bone mass in adolescents: the
 490 HELENA Study. *Eur J Appl Physiol* 111: 2671-2680, 2011.
- 491 25. **Hamilton B.** Vitamin d and athletic performance: the potential role of muscle. *Asian*
 492 *J Sports Med* 2: 211-219, 2011.
- 493 26. **Kimura M, Kanehira K, and Yokoi K.** Highly sensitive and simple liquid
 494 chromatographic determination in plasma of B6 vitamers, especially pyridoxal 5'-phosphate.
 495 *J Chromatogr A* 722: 296-301, 1996.
- 496 27. **Lawrence JD, Bower RC, Riehl WP, and Smith JL.** Effects of alpha-tocopherol
 497 acetate on the swimming endurance of trained swimmers. *Am J Clin Nutr* 28: 205-208,
 498 1975.
- 499 28. **Leger LA, Mercier D, Gadoury C, and Lambert J.** The multistage 20 metre
 500 shuttle run test for aerobic fitness. *J Sports Sci* 6: 93-101, 1988.
- 501 29. **Lukaski HC.** Vitamin and mineral status: effects on physical performance. *Nutrition*
 502 20: 632-644, 2004.
- 503 30. **Lloyd T, Chinchilli VM, Rollings N, Kieselhorst K, Tregoe DF, Henderson NA,**
 504 **and Sinoway LI.** Fruit consumption, fitness, and cardiovascular health in female
 505 adolescents: the Penn State Young Women's Health Study. *Am J Clin Nutr* 67: 624-630,
 506 1998.
- 507 31. **Moreno L.** Adolescence. In: *Pediatric Nutrition in Practice*, edited by Koletzko B.
 508 Basel: Karger, 2008, p. 114-117.
- 509 32. **Moreno LA, De Henauw S, Gonzalez-Gross M, Kersting M, Molnar D,**
 510 **Gottrand F, Barrios L, Sjostrom M, Manios Y, Gilbert CC, Leclercq C, Widhalm K,**
 511 **Kafatos A, and Marcos A.** Design and implementation of the Healthy Lifestyle in Europe

- 512 by Nutrition in Adolescence Cross-Sectional Study. *Int J Obes (Lond)* 32 Suppl 5: S4-11,
513 2008.
- 514 33. **Moreno LA, Gonzalez-Gross M, Kersting M, Molnar D, de Henauw S, Beghin**
515 **L, Sjostrom M, Hagstromer M, Manios Y, Gilbert CC, Ortega FB, Dallongeville J,**
516 **Arcella D, Warnberg J, Hallberg M, Fredriksson H, Maes L, Widhalm K, Kafatos AG,**
517 **and Marcos A.** Assessing, understanding and modifying nutritional status, eating habits and
518 physical activity in European adolescents: the HELENA (Healthy Lifestyle in Europe by
519 Nutrition in Adolescence) Study. *Public Health Nutr* 11: 288-299, 2008.
- 520 34. **Mowry DA, Costello MM, and Heelan KA.** Association among cardiorespiratory
521 fitness, body fat, and bone marker measurements in healthy young females. *J Am Osteopath*
522 *Assoc* 109: 534-539, 2009.
- 523 35. **Nagy E, Vicente-Rodriguez G, Manios Y, Beghin L, Iliescu C, Censi L, Dietrich**
524 **S, Ortega FB, De Vriendt T, Plada M, Moreno LA, and Molnar D.** Harmonization
525 process and reliability assessment of anthropometric measurements in a multicenter study in
526 adolescents. *Int J Obes (Lond)* 32 Suppl 5: S58-65, 2008.
- 527 36. **Novack V, Finestone AS, Constantini N, Shpilberg O, Weitzman S, and Merkel**
528 **D.** The prevalence of low hemoglobin values among new infantry recruits and nonlinear
529 relationship between hemoglobin concentration and physical fitness. *Am J Hematol* 82: 128-
530 133, 2007.
- 531 37. **Ortega FB, Artero EG, Ruiz JR, Espana-Romero V, Jimenez-Pavon D, Vicente-**
532 **Rodriguez G, Moreno LA, Manios Y, Beghin L, Ottevaere C, Ciarapica D, Sarri K,**
533 **Dietrich S, Blair SN, Kersting M, Molnar D, Gonzalez-Gross M, Gutierrez A, Sjostrom**
534 **M, and Castillo MJ.** Physical fitness levels among European adolescents: the HELENA
535 study. *Br J Sports Med* 45: 20-29, 2009.
- 536 38. **Ortega FB, Artero EG, Ruiz JR, Vicente-Rodriguez G, Bergman P, Hagstromer**
537 **M, Ottevaere C, Nagy E, Konsta O, Rey-Lopez JP, Polito A, Dietrich S, Plada M,**
538 **Beghin L, Manios Y, Sjostrom M, and Castillo MJ.** Reliability of health-related physical
539 fitness tests in European adolescents. The HELENA Study. *Int J Obes (Lond)* 32 Suppl 5:
540 S49-57, 2008.
- 541 39. **Ortega FB, Ruiz JR, Castillo MJ, and Sjostrom M.** Physical fitness in childhood
542 and adolescence: a powerful marker of health. *Int J Obes (Lond)* 32: 1-11, 2008.
- 543 40. **Perez-Lopez FR, Chedraui P, and Fernandez-Alonso AM.** Vitamin D and aging:
544 beyond calcium and bone metabolism. *Maturitas* 69: 27-36, 2011.
- 545 41. **Perez-Lopez FR, Fernandez-Alonso AM, Ferrando-Marco P, Gonzalez-**
546 **Salmeron MD, Dionis-Sanchez EC, Fiol-Ruiz G, and Chedraui P.** First trimester serum
547 25-hydroxyvitamin D status and factors related to lower levels in gravids living in the
548 Spanish Mediterranean coast. *Reprod Sci* 18: 730-736, 2011.
- 549 42. **Racinais S, Hamilton B, Li CK, and Grantham J.** Vitamin D and physical fitness
550 in Qatari girls. *Arch Dis Child* 95: 854-855, 2010.
- 551 43. **Ruiz JR, Castro-Pinero J, Espana-Romero V, Artero EG, Ortega FB, Cuenca**
552 **MM, Jimenez-Pavon D, Chillon P, Girela-Rejon MJ, Mora J, Gutierrez A, Suni J,**
553 **Sjostrom M, and Castillo MJ.** Field-based fitness assessment in young people: the ALPHA
554 health-related fitness test battery for children and adolescents. *Br J Sports Med* 45: 518-524,
555 2011.
- 556 44. **Ruiz JR, Ortega FB, Martinez-Gomez D, Labayen I, Moreno LA, De**
557 **Bourdeaudhuij I, Manios Y, Gonzalez-Gross M, Mauro B, Molnar D, Widhalm K,**
558 **Marcos A, Beghin L, Castillo MJ, and Sjostrom M.** Objectively Measured Physical
559 Activity and Sedentary Time in European Adolescents: The HELENA Study. *Am J*
560 *Epidemiol* 174: 173-184, 2011.

- 561 45. **Sharman IM, Down MG, and Sen RN.** The effects of vitamin E and training on
562 physiological function and athletic performance in adolescent swimmers. *Br J Nutr* 26: 265-
563 276, 1971.
- 564 46. **Shephard RJ, Campbell R, Pimm P, Stuart D, and Wright GR.** Vitamin E,
565 exercise, and the recovery from physical activity. *Eur J Appl Physiol Occup Physiol* 33:
566 119-126, 1974.
- 567 47. **Sorensen E, Grau K, Berg T, Simonsen AC, Magnussen K, Erikstrup C, Hansen**
568 **MB, and Ullum H.** A genetic risk factor for low serum ferritin levels in Danish blood
569 donors. *Transfusion* 2012 doi: 10.1111/j.1537-2995.2012.03629.x.
- 570 48. **Suboticanec-Buzina K, Buzina R, Brubacher G, Sapunar J, and Christeller S.**
571 Vitamin C status and physical working capacity in adolescents. *Int J Vitam Nutr Res* 54: 55-
572 60, 1984.
- 573 49. **Tomkinson GR.** Global changes in anaerobic fitness test performance of children
574 and adolescents (1958-2003). *Scand J Med Sci Sports* 17: 497-507, 2007.
- 575 50. **Tomkinson GR, and Olds TS.** Secular changes in pediatric aerobic fitness test
576 performance: the global picture. *Med Sport Sci* 50: 46-66, 2007.
- 577 51. **Tussing-Humphreys LM, Liang H, Nemeth E, Freels S, and Braunschweig CA.**
578 Excess adiposity, inflammation, and iron-deficiency in female adolescents. *J Am Diet Assoc*
579 109: 297-302, 2009.
- 580 52. **Valtuna J, Breidenassel C, Folle J, and Gonzalez-Gross M.** Retinol, beta-
581 carotene, alpha-tocopherol and vitamin D status in European adolescents; regional
582 differences and variability: A review. *Nutr Hosp* 26: 280-288, 2011.
- 583 53. **Victora CG, Huttly SR, Fuchs SC, and Olinto MT.** The role of conceptual
584 frameworks in epidemiological analysis: a hierarchical approach. *Int J Epidemiol* 26: 224-
585 227, 1997.
- 586 54. **Wang J, Huo JS, Sun J, and Ning ZX.** Physical performance of migrant
587 schoolchildren with marginal and severe iron deficiency in the suburbs of Beijing. *Biomed*
588 *Environ Sci* 22: 333-339, 2009.
- 589 55. **Ward KA, Das G, Berry JL, Roberts SA, Rawer R, Adams JE, and Mughal Z.**
590 Vitamin D status and muscle function in post-menarchal adolescent girls. *J Clin Endocrinol*
591 *Metab* 94: 559-563, 2009.
- 592 56. **Zoppi CC, Hohl R, Silva FC, Lazarim FL, Neto JM, Stancanneli M, and**
593 **Macedo DV.** Vitamin C and e supplementation effects in professional soccer players under
594 regular training. *J Int Soc Sports Nutr* 3: 37-44, 2006.
- 595
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Table 1. Descriptive characteristics of the studied adolescents by sex.

Variables	Males				Females				
	n	Mean	SD	n	Mean	SD	n	Mean	SD
Age (y)	509	15.02	± 1.23	580	15.04	± 1.18			
Body mass (kg)	509	62.8	± 14.4	580	56.3	± 10.1			
Height (cm)	509	170.2 (163.8-177)		580	162 (157.5-166.6)				
BMI (kg/m ²)	509	21.5	± 4.0	580	21.4	± 3.4			
Seasonality (Winter/autumn/spring) (%)	509	(28/31/41)		580	(24/33/43)				
MVPA (min/day)	318	69.0	± 25.1	395	51.5	± 20.5			
SLJ (cm)	463	184.7	± 32.9	537	144.8	± 25.6			
VO _{2max} (ml/Kg/min)	404	44.2	± 7.9	428	36.0	± 5.4			
Iron status									
Hemoglobin (g/dL)	508	14.7	± 1.2	569	13.4	± 1.1			
sTfR (mg/L)	469	5.9 (4.7-7.0)		536	5.7 (4.5-7.1)				
Serum ferritin (µg/L)	477	32.8 (18.2-50.0)		532	24.4 (14.1-38.7)				
Antioxidant vitamins									
β-carotene (ng/ml)	452	192.5 (130.8-279.2)		506	219.9 (148.6-311.3)				
Retinol (ng/ml)	445	349.7 (282.7-411.5)		501	325.5 (277.0-402.2)				
α-tocopherol (µg/ml)	447	9.5	± 1.9	507	10.3	± 2.1			
Vitamin C (mg/L)	503	10.03	± 3.28	554	10.64	± 3.31			
Hidrosoluble vitamins									
Vitamin B ₆ (pmol/L)	453	53.7 (37.9-79.3)		528	46.5 (32.1-70.1)				
Cobalamin (pmol/L)	501	328.39	± 125.26	554	368.28	± 155.31			
Holo-Transcobalamin (pmol/L)	469	58.7 (44.2-72.1)		551	57.7 (45.3-74.5)				
Plasma folate (nmol/L)	497	16.0 (11.8-22.1)		552	16.2 (12.2-22.8)				
RBC folate (nmol/L)	495	728.5 (568.5-952.9)		545	707.9 (544.4-931.6)				
Vitamin D									
25(OH)D (nmol/L)	471	57.38	± 22.63	538	60.20	± 23.41			

25(OH)D, 25-hydroxyvitamin D; **MVPA**, moderate to vigorous physical activity; **RBC**, red blood cells; **SD**, standard deviation; **SLJ**, standing long jump; **sTfR**, soluble transferrin receptor; **VO_{2max}**, maximal oxygen consumption
ANOVA was performed for normally distributed variables (mean ± SD) and *U* Mann Whitney for non-normally distributed variables (median and interquartil intervals)

Table 2. Association of micronutrient-related biomarker status and potential confounders with cardiorespiratory fitness (VO_{2max} , ml/kg/min) in male European adolescents.

Males - VO_{2max}							
Model	Variables	Unadjusted analysis			Adjusted analysis		
		β	P	n	β	P*	n
1 ^a	Age	-0.186	<0.001	404	-0.217	<0.001	
	Seasonality	0.139	0.005	404	0.135	0.003	404
	Latitude	0.311	<0.001	404	0.324	<0.001	
2 ^a	BMI	-0.445	<0.001	404	-0.374	<0.001	404
3 ^a	MVPA	0.329	<0.001	264	0.205	<0.001	264
4 ^b	Hemoglobin	-0.010	0.836	400	0.192	0.002	
	sTfR †	0.000	0.995	376	-0.010	0.861	246
	Serum ferritin ‡	-0.149	0.003	384	-0.022	0.700	
5 ^c	β -carotene †	0.210	<0.001	355	-0.048	0.481	
	Retinol †	-0.080	0.133	349	0.148	0.031	221
	α -tocopherol	0.007	0.895	349	-0.050	0.417	
	Vitamin C	0.173	0.001	400	0.186	0.005	
6 ^d	Vitamin B ₆ †	0.042	0.425	358	0.058	0.363	
	Cobalamin †	0.162	0.001	396	0.084	0.261	
	Holo-Transcobalamin †	0.090	0.086	369	-0.031	0.689	222
	Plasma folate †	0.019	0.713	394	-0.004	0.964	
	RBC folate †	0.049	0.329	392	-0.008	0.925	
7 ^e	25(OH)D	0.113	0.029	372	0.088	0.127	250

β is the standardized regression coefficient.

^a The effect of each variable on the outcome was adjusted for other variables in the same model or above in the hierarchical model

^b Significant variables shown in models 1-3 + model 4 were included

^c Significant variables shown in models 1-3 + model 5 were included

^d Significant variables shown in models 1-3 + model 6 were included

^e Significant variables shown in models 1-3 + model 7 were included

† Log-transformed data; ‡ Square-root transformed data

* Variables with P > 0.2 were not included in the subsequent adjustment models

BMI, body mass index; **25(OH)D**, 25-hydroxyvitamin D; **MVPA**, moderate to vigorous physical activity; **RBC**, red blood cells; **sTfR**, soluble transferrin receptor; **VO_{2max}**, maximal oxygen consumption.

Categorical variables: Seasonality (1= winter, 2= autumn, 3= spring); MVPA (0= <60 min/day, 1= ≥ 60 min/day)

Table 3. Association of micronutrient-related biomarker status and potential confounders with cardiorespiratory fitness (VO_{2max} , ml/kg/min) in female European adolescents.

		Females - VO_{2max}					
		Unadjusted analysis			Adjusted analysis		
Model	Variables	β	P	n	β	P*	n
1^a	Age	-0.445	< 0.001	427	-0.492	< 0.001	
	Seasonality	0.213	< 0.001	424	0.224	< 0.001	424
	Latitude	0.178	< 0.001	428	0.233	< 0.001	
2^a	BMI	-0.321	< 0.001	428	-0.226	< 0.001	419
	Menarche	-0.380	< 0.001	425	-0.101	0.039	
3^a	MVPA	0.100	0.039	296	0.039	0.413	290
4^b	Hemoglobin	0.041	0.401	418	0.038	0.390	
	sTfR †	0.022	0.661	390	-0.039	0.374	377
	Serum ferritin ‡	0.002	0.973	389	0.006	0.887	
5^c	β -carotene †	0.189	< 0.001	371	0.101	0.042	354
	Retinol †	-0.004	0.934	364	0.064	0.214	
	α -tocopherol	0.041	0.432	364	-0.029	0.540	
	Vitamin C	0.069	0.161	417	0.013	0.779	
6^d	Vitamin B ₆ †	0.130	0.010	388	0.026	0.572	366
	Cobalamin †	0.203	< 0.001	403	0.016	0.785	
	Holo-Transcobalamin †	0.102	0.040	409	0.067	0.231	
	Plasma folate †	0.108	0.030	402	-0.051	0.387	
	RBC folate †	0.109	0.030	398	0.084	0.156	
7^e	25(OH)D	0.027	0.593	396	0.091	0.030	391

β is the standardized regression coefficient

^a The effect of each variable on the outcome was adjusted for other variables in the same model or above in the hierarchical model

^b Significant variables shown in models 1-3 + model 4 were included

^c Significant variables shown in models 1-3 + model 5 were included

^d Significant variables shown in models 1-3 + model 6 were included

^e Significant variables shown in models 1-3 + model 7 were included

† Log-transformed data; ‡ Square-root transformed data

* Variables with $P > 0.2$ were not included in the subsequent adjustment models

BMI, body mass index; **25(OH)D**, 25-hydroxyvitamin D; **MVPA**, moderate to vigorous physical activity; **RBC**, red blood cells; **sTfR**, soluble transferrin receptor; **VO_{2max}**, maximal oxygen consumption.

Categorical variables: Seasonality (1= winter, 2= autumn, 3= spring); MVPA (0= <60 min/day, 1= \geq 60 min/day)

Table 4. Association of micronutrient-related biomarker status and potential confounders with muscular fitness (SLJ, cm) in male European adolescents.

Males - SLJ							
Model	Variables	Unadjusted analysis			Adjusted analysis		
		β	P	n	β	P*	n
1 ^a	Age	0.382	<0.001	462	0.372	<0.001	
	Seasonality	0.001	0.983	463	-0.044	0.294	462
	Latitude	0.288	<0.001	463	0.273	<0.001	
2 ^a	BMI	-0.256	<0.001	463	-0.291	<0.001	462
3 ^a	MVPA	0.142	0.014	300	0.132	0.010	300
4 ^b	Hemoglobin	0.286	<0.001	459	0.203	0.001	
	sTfR †	-0.109	0.025	426	-0.007	0.897	273
	Serum ferritin ‡	0.105	0.029	433	0.080	0.156	
5 ^c	β -carotene †	0.227	<0.001	412	0.160	0.013	
	Retinol †	0.241	<0.001	404	0.128	0.039	254
	α -tocopherol	-0.063	0.204	404	-0.135	0.017	
	Vitamin C	0.109	0.019	458	-0.003	0.965	
6 ^d	Vitamin B ₆ †	0.024	0.631	414	0.030	0.619	
	Cobalamin †	0.035	0.461	454	0.014	0.846	
	Holo-Transcobalamin †	-0.005	0.910	424	0.091	0.213	252
	Plasma folate †	-0.113	0.016	453	0.028	0.721	
	RBC folate †	0.005	0.912	451	-0.088	0.267	
7 ^e	25(OH)D	0.078	0.105	430	0.085	0.120	285

β is the standardized regression coefficient

^a The effect of each variable on the outcome was adjusted for other variables in the same model or above in the hierarchical model

^b Significant variables shown in models 1-3 + model 4 were included

^c Significant variables shown in models 1-3 + model 5 were included

^d Significant variables shown in models 1-3 + model 6 were included

^e Significant variables shown in models 1-3 + model 7 were included

† Log-transformed data; ‡ Square-root transformed data

* Variables with P > 0.2 were not included in the subsequent adjustment models

BMI, body mass index; **25(OH)D**, 25-hydroxyvitamin D; **MVPA**, moderate to vigorous physical activity; **RBC**, red blood cells; **SLJ**, standing long jump; **sTfR**, soluble transferrin receptor.

Categorical variables: Seasonality (1= winter, 2= autumn, 3= spring); MVPA (0= <60 min/day, 1= ≥ 60 min/day)

Table 5. Association of micronutrient-related biomarker status and potential confounders with muscular fitness (SLJ, cm) in female European adolescents.

		Females - SLJ					
		Unadjusted analysis			Adjusted analysis		
<i>Model</i>	<i>Variables</i>	β	<i>P</i>	<i>n</i>	β	<i>P*</i>	<i>n</i>
1^a	Age	0.177	<0.001	536	0.142	0.001	
	Seasonality	0.052	0.231	531	0.000	0.998	531
	Latitude	0.299	<0.001	537	0.284	<0.001	
2^a	BMI	-0.336	<0.001	537	-0.313	<0.001	532
	Menarche	-0.037	0.400	533	-0.082	0.090	
3^a	MVPA	0.143	0.006	373	0.108	0.021	369
4^b	Hemoglobin	-0.032	0.463	526	0.008	0.878	
	sTfR †	0.045	0.319	491	0.058	0.280	329
	Serum ferritin ‡	-0.095	0.036	489	-0.020	0.709	
5^c	β -carotene †	0.257	<0.001	470	0.177	0.003	305
	Retinol †	-0.048	0.298	464	-0.080	0.182	
	α -tocopherol	0.029	0.534	465	0.003	0.954	
	Vitamin C	0.114	0.009	512	-0.019	0.727	
6^d	Vitamin B ₆ †	0.056	0.218	492	0.087	0.099	
	Cobalamin †	0.060	0.179	511	0.046	0.488	
	Holo-Transcobalamin †	0.035	0.426	512	0.036	0.581	326
	Plasma folate †	-0.004	0.931	510	-0.058	0.383	
	RBC folate †	0.030	0.508	505	0.084	0.223	
7^e	25(OH)D	0.081	0.070	501	0.125	0.010	350

β is the standardized regression coefficient

^a The effect of each variable on the outcome was adjusted for other variables in the same model or above in the hierarchical model

^b Significant variables shown in models 1-3 + model 4 were included

^c Significant variables shown in models 1-3 + model 5 were included

^d Significant variables shown in models 1-3 + model 6 were included

^e Significant variables shown in models 1-3 + model 7 were included

† Log-transformed data; ‡ Square-root transformed data

* Variables with $P > 0.2$ were not included in the subsequent adjustment models

BMI, body mass index; **25(OH)D**, 25-hydroxyvitamin D; **MVPA**, moderate to vigorous physical activity; **RBC**, red blood cells; **SLJ**, standing long jump; **sTfR**, soluble transferrin receptor.

Categorical variables: Seasonality (1= winter, 2= autumn, 3= spring); MVPA (0= <60 min/day, 1= \geq 60 min/day)