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Female athlete representation and dietary control methods among studies assessing chronic carbohydrate approaches to support training

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Running Head: Female representation in carbohydrate research

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1 **Abstract**

2 The aim of this audit was to assess the representation of female athletes, dietary control methods
3 and gold-standard female methodology that underpins the current guidelines for chronic
4 carbohydrate (CHO) intake strategies for athlete daily training diets. Using a standardized audit,
5 281 studies were identified that examined high versus moderate CHO, periodized CHO
6 availability, and/or low CHO, high fat diets. There were 3,735 total participants across these
7 studies with only ~16% of participants being women. Few studies utilised a design that
8 specifically considered females, with only 16 studies (~6%) including a female-only cohort and 6
9 studies (~2%) with a sex-based comparison in their statistical procedure, in comparison to the
10 217 studies (~77%) including a male-only cohort. Most studies (~72%) did not provide sufficient
11 information to define the menstrual status of participants, and of the 18 studies that did, optimal
12 methodology for control of ovarian hormones was only noted in 1 study. While ~40% of male-
13 only studies provided all food and beverages to participants, only ~20% of studies with a female-
14 specific design used this approach for dietary control. Most studies did not implement strategies
15 to ensure compliance to dietary interventions and/or control energy intake during dietary
16 interventions. The literature that has contributed to the current guidelines for daily CHO intake is
17 lacking in research that is specific to, or adequately addresses, the female athlete. Redressing this
18 imbalance is of high priority to ensure that the female athlete receives evidence-based
19 recommendations that consider her specific needs.

20 **Keywords:** women, audit, periodized, carbohydrate availability, low carbohydrate, high fat,
21 menstrual status

22 **Introduction**

23 Guidelines for carbohydrate (CHO) intake in the athlete's everyday training diet have been a
24 central and evolving theme over the 60-year history of sports nutrition. Whereas early guidelines
25 promoted high absolute intakes of CHO based on maximising rates of daily glycogen storage
26 (Coyle, 1991), more recent approaches support individualized and periodized intakes to match
27 the needs of the changing training loads, or to target different acute sessions with high or low
28 CHO availability according to the priority of performance or enhanced adaptation (Burke et al.,
29 2018). In addition, there has been interest in the effects of chronic adaptation to low CHO, high
30 fat (LCHF) diets with a goal of possibly enhancing competition performance via reduced
31 reliance on the relatively limited CHO stores as the key substrate for exercise.

32 Studies have investigated the effects of these different dietary approaches on exercise
33 metabolism, adaptation to training, and exercise capacity/performance. For instance,
34 investigations of LCHF dietary approaches have failed to provide evidence of a performance
35 enhancing benefit over traditional CHO recommendations for athletes (Burke, 2021). However,
36 there is increasing awareness that research across various areas of sports science and medicine is
37 predominantly conducted in male populations (Cowley et al., 2021; Smith et al., 2022c). This
38 creates uncertainty around the application of the results to female athletes due to sex-based
39 physiological, morphological and performance differences (Hilton & Lundberg, 2021;
40 Tarnopolsky, 2008; Wells, 2007; Yanovich et al., 2020). For instance, sex differences exist in
41 body composition with a ~45% greater magnitude in lean body mass, and ~30% less fat mass in
42 men compared to women (Hilton & Lundberg, 2021). Yet, current CHO guidelines are expressed
43 relative to body mass and do not consider sex difference in body composition, which could
44 impact the ability to store consumed CHO. Furthermore, when women are included in such

45 studies, it is unclear if the physiological changes, which occur over the menstrual cycle or via
46 alterations to ovarian hormones due to scenarios such as hormonal contraceptive usage, have
47 been considered (Elliott-Sale et al., 2021). Failure to follow best-practice guidelines for the
48 methodological control of ovarian hormones may result in erroneous findings and
49 recommendations (Elliott-Sale et al., 2021; Janse de Jong et al., 2019).

50 We recently conducted an audit of the literature from which guidelines for acute strategies to
51 manipulate CHO availability around a single session of exercise have been derived (Kuikman et
52 al., 2022). Therein we showed both a dearth of female participants and poor attention to
53 hormonal characterization and standardization in the studies that included females. Whether
54 there is even greater under-representation within literature supporting current guidelines for
55 chronic approaches to CHO intake that are incorporated into the daily training diet of an athlete
56 is of interest. The longitudinal nature of these studies creates even greater challenges in
57 controlling for ovarian hormones, since measurements may extend over multiple phases of the
58 menstrual cycle, or with hormonal contraceptive regimens. Additionally, the prolonged
59 commitment required for these studies may contribute to volunteer bias such that there may be
60 sex differences in willingness to participate in this research, resulting in a greater difficulty in
61 recruiting female participants for study involvement (Nuzzo, 2021). Female athletes may be
62 particularly reluctant to participate in projects that focus on chronic CHO intake and involve
63 periods of prolonged dietary control due to increased rates of disordered eating in female athletes
64 compared to male athletes (Bratland-Sanda & Sundgot-Borgen, 2013). Furthermore, female
65 athletes are more likely to consume lower/sub-optimal CHO intakes (Burke et al., 2001) or fail to
66 adjust intakes according to changes in daily training (Heikura et al., 2018). While the cause of

67 this is likely multifactorial, inadequate CHO intake may be secondary to inadequate energy
68 intake (Burke et al., 2001).

69 We were interested in studies assessing chronic CHO intake strategies that are incorporated into
70 an athlete's daily diet and consequently influence and must consider daily energy intake, as
71 failure to do so could confound study results. Chronic CHO intake strategies assessed included
72 studies that compare habitual/moderate CHO intakes versus higher CHO diets, studies of
73 periodized approaches to CHO availability (P-CHO) in training, and studies of LCHF diets.
74 Accordingly, this project employed a standardized auditing tool (Smith et al., 2022a) to assess
75 the male versus female representation in studies assessing these strategies. The dietary control
76 methods implemented within these studies were also assessed to provide information on possible
77 barriers that contribute to inequities in female inclusion and factors that may result in either
78 erroneous or consensus findings.

79 **Methods**

80 The methods of this audit are in accordance with a standardized protocol (Smith et al., 2022a)
81 with an electronic search from inception to January 18, 2022 being conducted in PubMed.
82 Methods specific to this audit are outlined below.

83 *Data Selection and Extraction*

84 After removal of duplicates, papers were screened using Rayyan online software (Ouzzani et al.,
85 2016) to identify papers that met inclusion criteria. Studies were included if the primary
86 investigation involved the effects of the various approaches to chronic CHO intake on a
87 performance outcome, health outcome or underlying mechanism (Table 1). Studies using
88 statistical methodology to examine more than one approach were classified into all applicable
89 categories.

90 -Table 1-

91 During data extraction, two authors independently classified papers into a chronic CHO intake
92 fuelling strategy and a third author resolved any conflicts. The following were exclusion criteria:
93 participants were >50 years and untrained, children, were not explicitly described by sex or had
94 lifestyle diseases; the study involved an occupational task (e.g., soldiers, firefighters), the CHO-
95 based intervention was the control condition and the investigation/outcome was irrelevant to the
96 area of interest (Figure 1). Papers examining the effects of an acute CHO fuelling strategy were
97 included in a sister analysis (Kuikman et al., 2022).

98 -Figure 1-

99 For articles that met inclusion criteria, data were extracted into Microsoft Excel and included
100 retrieving the following metrics:

101 *A. Study Design:* females-only, males-only, mixed-sex cohort, male versus female design
102 features (MvFdes), and male versus female sub-analysis (MvFsub).

103 *B. Athletic Caliber as previously established (McKay et al., 2022):* Tier 0 (Sedentary), Tier 1
104 (Recreationally Active), Tier 2 (Trained/Developmental), Tier 3 (Highly trained/National), Tier
105 4 (Elite/International), and Tier 5 (World-Class).

106 *C. Menstrual Status and Grade:* Naturally menstruating or eumenorrhic women, hormonal
107 contraceptive users, women with menstrual irregularities, mixture of one of the aforementioned
108 categories with studies then being graded as Gold, Silver, Bronze, or Ungraded standard based
109 on methodological control of ovarian hormones as per Best Practice Guidelines (Elliott-Sale et
110 al., 2021). Supplementary table 1 outlines the full criteria as per Smith et al., (2022a) that was

111 used to grade studies. With this grading protocol, if insufficient information was provided to
112 determine menstrual status, then studies were defined as unclassified and were not graded.

113 *D. Research Theme:* Primary focus on performance outcome, clinically established health
114 outcome, or indirect or emerging associations with performance or health.

115 *E. Study Impact:* Altmetric score and most recent 4-year impact factor (IF). Altmetric scores
116 were only retrieved for studies published after 2012 and obtained between December 23, 2021-
117 January 18, 2022.

118 *F. Sample Size:* Male and female participant number.

119 Studies that included a female specific design (females only, MvFdes, and MvFsub), enabling
120 outcomes to contribute knowledge about sex-based differences or directly inform female-specific
121 guidelines, were examined to determine methods of implementation of the dietary strategy;
122 protocols to verify adherence to the strategy; and protocols used to set the energy characteristics
123 of interventions. Male-only studies that implemented dietary control by providing all food and
124 beverages to participants were also identified for comparison, since this is both the most highly
125 controlled and resource-intensive methodology (Jeacocke & Burke, 2010). We noted the
126 duration of the dietary intervention, including standardized dietary intake periods. In the case of
127 cross-over designs, this involved the cumulative length of all dietary interventions excluding
128 periods in which participants consumed their habitual diet. Dietary control periods of <24 hrs
129 and case studies were not included here.

130 Statistics

131 Statistical analyses were performed using R Studio (v3.5.2) with significance accepted at an α
132 level of $p \leq 0.05$. Frequency-based metrics were reported as a percentage of the total studies or

133 participants. Histogram inspection revealed all outcomes were non-normally distributed data. A
134 Mann Whitney U-Test was used to compare median number of male to female participants
135 across study design, while a Kruskal Wallis Test with a post-hoc Dunn test assessed differences
136 in IF, altmetric scores, and length of dietary interventions across study design. Data are reported
137 as median \pm interquartile range.

138 **Results**

139 A total of 281 studies were included across the three chronic CHO fuelling strategies. These
140 involved a total of 3,735 participants with ~16% and ~84% being female and male participants,
141 respectively (Figure 2). While ~94% of studies (n = 265) included at least 1 male participant,
142 only ~23% of studies (n = 64) included at least 1 female participant.

143 -Figure 2-

144 *Study Design and Sample Size*

145 Across the different research categories, 16 studies (~6%) included a female-only design
146 compared with 217 studies (~77%) that included a male-only design (Figure 3). Two studies
147 (~0.7%) conducted a sex-based comparison (MvFsub) within the statistical procedure, and only 4
148 studies (~1%) included methodological designs (MvFdes) specifically comparing sex-based
149 responses. Of the 22 studies with a female-specific design (female-only, MvFdes, or MvFsub),
150 the majority examined LCHF diets (~73%, n = 16), while 5 studies compared moderate versus
151 high (MvH) diets, and 1 study assessed P-CHO diets. Of the 64 studies that included female
152 participants, most involved a mixed-sex cohort (~66%, n = 42). For studies with a mixed-sex
153 cohort, the median number of male participants was 9 ± 12 whereas the median number of

154 female participants was 6 ± 4 ($p = 0.01$). The median number of male and female participants
155 was similar across other study designs.

156 -Figure 3-

157 *Research Theme and Athlete Caliber*

158 Most studies assessing LCHF diets (~53%, $n = 79$) and MvH diets (~63%, $n = 29$) investigated
159 performance themes, whereas studies of P-CHO diets mostly examined indirect markers of
160 health or performance (~60%, $n = 52$; Figure 4). No study was found to primarily investigate a
161 health outcome according to the definition of Smith et al., 2022a. Of the 281 studies, 130 studies
162 (~46%) failed to provide sufficient information to classify the caliber of athletes. For the
163 remaining 151 studies, ~72% of participants were classified within Tier 0 (Sedentary) to Tier 2
164 (Trained/developmental). Tier 2 (Trained/developmental) athletes represented the majority of
165 participants in studies of LCHF diets (~44%; $n = 34$) and MvH diets (~47%; $n = 14$), whereas
166 Tier 1 (Recreationally Active) participants were primarily used to study P-CHO diets (~40%, $n =$
167 17). The one study involving Tier 5 athletes investigated a LCHF diet (Mujika, 2019).

168 -Figure 4-

169 *Publication Statistics*

170 The IF ($p = 0.34$) and altmetric score ($p = 0.75$) was similar between the 5 study designs and this
171 remained similar when differences between study designs were examined for each of the three
172 daily CHO fuelling strategies in isolation. The yearly publication rate from 1970-2021 of male-
173 only studies was 4 studies/yr whereas the yearly publication rate of female-only studies was 0.3
174 studies/yr (see Figure 5).

175 -Figure 5-

176 *Menstrual Status and Control*

177 Most (72%) of the 64 studies that included women provided insufficient information to define
178 the menstrual status of participants. Of the 18 studies that menstrual status was defined, 15
179 involved naturally menstruating women, and three included both naturally menstruating women
180 and hormonal contraceptive users. Six studies described participants as being eumenorrheic
181 although none met the gold-standard methodological criteria for defining eumenorrhea (Elliott-
182 Sale et al., 2021), and 1 study inappropriately referred to hormonal contraceptive users as
183 eumenorrheic. Within the three studies that included hormonal contraceptive users, two
184 described the use of oral contraceptive pills while the other failed to provide information on the
185 type of hormonal contraceptive. The only study with recognized methodological control of
186 ovarian hormones involved a mixture of naturally menstruating women and hormonal
187 contraceptive users (Figure 6), with the hormonal contraceptive users (0.5 of the study) being
188 awarded Bronze standard and naturally menstruating females remaining ungraded (Duhamel et
189 al., 2006). This resulted in 17.5 ungraded studies.

190 -Figure 6-

191 *Menstrual and Hormonal Cycle Phase*

192 Five studies described the standardized collection of study outcomes in the follicular phase of the
193 menstrual cycle, while one study undertook investigations in the luteal phase. Two studies
194 indicated measurements were always taken in the same phase of the menstrual cycle but did not
195 identify the phase, while eight studies failed to provide information regarding timing of data
196 collection according to menstrual cycle phase. Two of the studies with hormonal contraceptive

197 users failed to identify the phase in which measurements were taken and one used confusing
198 terminology by indicating that measurements were taken in the “mid-follicular phase.” Finally,
199 two studies assessed a daily CHO fuelling strategy across menstrual cycle phase with both
200 comparing the mid-follicular and mid-luteal phase of the menstrual cycle.

201 *Dietary Control*

202 The duration of dietary interventions was 21 ± 39.5 days for female only studies, 14 ± 22 days
203 for male only studies, 21 ± 32 days for mixed cohort studies, 28 ± 5 days for MvFdes studies,
204 and 17 ± 11 days for MvFsub studies ($p = 0.089$). The length of dietary interventions between
205 study designs remained similar when each chronic CHO fuelling strategy was assessed in
206 isolation. Different protocols were used across studies to implement and verify the dietary
207 interventions (Figure 7). Of studies with a female-specific design ($n = 22$), 4.5 (~20%) provided
208 participants with all food/beverages. The 0.5 outcome denotes a study in which one group was
209 provided with food while the other followed a meal plan (Berend et al., 1994). This contrasts
210 with male-only studies, 40% of which directly provided participants with the dietary
211 intervention. Various protocols were used to determine the energy content of dietary treatments
212 and verify compliance with the intervention. Studies in which insufficient information or poor
213 practices were identified, leaving 11 studies with a female-specific design with sufficient dietary
214 control practices (Figure 7).

215 -Figure 7-

216 **Discussion**

217 We assessed the representation of female athletes in studies investigating different approaches to
218 CHO intake in the daily training diet, and the methodological control of ovarian hormones and

219 dietary intervention strategies employed within. Similar to other sports nutrition themes (Smith
220 et al., 2022c), women were vastly outnumbered, representing only ~16% of participants (598
221 females vs. 3,137 males across 281 studies) among the studies that underpin the current global
222 consensus recommendations for daily CHO intake (Burke et al., 2011; Burke et al., 2018). This
223 was a slightly higher proportion than found in the sister audit (Kuikman et al., 2022) of studies
224 assessing acute CHO fuelling strategies (~11%). Sixty-six percent of female participants were
225 involved in studies of mixed-design, which fail to add specific knowledge about the female
226 athlete and any difference in requirements to her male counterpart. Indeed, only ~5% of studies
227 included a female-only cohort, and ~1% were specifically designed to examine sex-based
228 differences. Similar to the audit of the literature on acute CHO fuelling, we found a smaller
229 median number of female than male participants in studies with a mixed-sex design. This may
230 reflect the addition of women to simply increase the total sample size and statistical power of
231 these studies, or a sex-based volunteer bias that makes it more difficult to recruit female
232 participants (Nuzzo, 2021).

233 *Methodological Control of Ovarian Hormones*

234 Only ~31% of studies (n = 18) provided sufficient information to define the menstrual status of
235 female participants, and only 0.5 (one cohort within a two-population study) described
236 methodological control of ovarian hormones to meet Best Practice Guidelines (Elliott-Sale et al.,
237 2021). Many studies used poor and confusing terminology, such as describing participants as
238 eumenorrheic despite failing to provide evidence to meet the gold-standard methodological
239 criteria (Elliott-Sale et al., 2021). This may reflect failure of researchers to value the importance
240 of controlling for ovarian hormones, and/or poor knowledge of the menstrual cycle and hormonal
241 contraceptives. Although this is a general finding across many research themes (Smith et al.,

242 2022a; 2022b), the chronic nature of the dietary interventions included in the current audit merits
243 separate comment. The average duration of dietary interventions for studies with naturally
244 menstruating females was ~20 days. As a result, these studies likely crossed over multiple phases
245 of the menstrual cycle, adding expense and logistical challenges to attempts to control for
246 ovarian hormones. Despite this, eight studies (~13%) managed to standardize the menstrual cycle
247 phase during which study outcomes were measured. Methods to achieve this included the
248 implementation of dietary interventions that extended across the entire duration of one or more
249 menstrual cycles (Valsdottir et al., 2019; Vargas-Molina et al., 2020, 2021), or the use of a
250 washout period to allow repeated measure designs to be conducted during the same phase of
251 consecutive menstrual cycles (Berend et al., 1994; Dolins et al., 2003; Duhamel et al., 2006;
252 Kłapcińska et al., 2002), or in the same phase of a single menstrual cycle (Lynch et al., 2000).
253 We recognize that some research scenarios and designs preclude the implementation of ideal
254 control for the menstrual or hormonal contraceptive phase of participants. Research-embedded
255 training camps with simultaneous participation of large groups of athletes, all starting on the
256 same day, make it very unlikely for athletes to synchronise their menstrual phase or hormonal
257 contraceptive use. This can be particularly challenging with elite to world-class athlete cohorts
258 who are unable to shift/change elements of training and timing of training camps. Furthermore,
259 depending on the research question, it may not be necessary to verify and control the menstrual
260 or hormonal contraceptive phase of participants, which will also improve ecological validity. In
261 these situations, or when it is not possible to standardize the phase of the menstrual or hormonal
262 contraceptive cycle, researchers should still characterize the menstrual status of participants
263 according to Best Practice Guidelines (Elliott-Sale et al., 2021) and note why standardization

264 was not possible. This was poorly done in the studies included in the current audit, with the
265 majority (~72%) failing to provide sufficient information.

266 *Dietary Control Methods*

267 The methods used to implement and monitor dietary protocols in chronic intervention studies are
268 of interest because they: 1) contribute a major time and resource cost to the study (which might
269 need to be balanced against other costs, such as tracking menstrual status); 2) present a barrier
270 for recruitment of female participants by removing dietary freedoms or instigating food
271 monitoring to individuals who have poor relationships with nutrition and self-image; and/or 3)
272 contribute to poor study methodology and erroneous findings. In the current audit, we showed no
273 differences in the length of the dietary interventions across various study designs, and a trend
274 towards a greater proportion (albeit low absolute number) of studies involving >20 d duration
275 within female-only (~56%, n = 9) compared to male-only studies (~34%, n = 80). This suggests
276 that the length of the dietary intervention is not a barrier for female participation in research. It
277 may also reflect that the majority of female-only studies examined LCHF diets (~82%), in which
278 a period of keto-adaptation of at least 3-4 w is recommended (Burke, 2021). A greater proportion
279 of male-only studies (~40%) than female-only studies (~19%) provided participants with all food
280 and beverages according to their dietary intervention, as is considered the gold standard for
281 achieving dietary control (Jeacocke & Burke, 2010). Perhaps female participants are less willing
282 to participate in projects involving this level of dietary control or maybe the funding and
283 resources for female-only studies cannot meet the required increase in time, cost and logistical
284 challenges associated with such methodologies. Interestingly, while the percent of published
285 studies that provided all food to participants increased from 33% (n = 74) in 1981-2001 to 50%

286 (n = 80) from 2001-2010, this decreased back to 33% (n = 43) from 2011-2022, suggesting that
287 there has not been an improvement in best practices for dietary control in more recent years.

288 Investigations that provide all food and beverages to participants generally achieve good
289 compliance to study interventions (Hall & Most, 2005), especially in scenarios such as metabolic
290 wards or research-embedded training camps (Mirtschin et al., 2018) where food intake can be
291 well-monitored and supervised. Among female-specific studies in the current audit, other
292 protocols to achieve the intervention of interest included provision of menus or nutrition
293 education to enable participants to implement their own intervention. In most cases, researchers
294 undertook protocols to verify the level of adherence to the diet(s) of interest; this included
295 supervision of meals as well as scrutiny of self-reports and food records in which the potential
296 for misreporting is recognised (Jeacocke & Burke, 2010). A few studies (n = 4) failed to provide
297 information on compliance to the study intervention. This is concerning, as study outcomes may
298 be attenuated because of discrepancies between the intended intervention and participants' actual
299 food intake (Most et al., 2003).

300 Energy intake (EI) and exercise energy expenditure (EEE) represent separate, but important,
301 characteristics of the study intervention. If EI and EEE are unknown, the measured outcome of
302 the CHO manipulation may be due to significantly altered energy availability (EA), confounding
303 the specific CHO-related research question. This has been demonstrated in other sports science
304 topics, such as the outcomes of training interventions, which fail to adjust the EI of athletes
305 involved (Stellingwerff et al., 2021). Furthermore, women may be more susceptible to the
306 physiological effects of problematic low EA compared to their male counterparts (Koehler et al.,
307 2016; Papageorgiou et al., 2017). Among the 16 female-specific studies included in the audit for
308 which adequate dietary control was implemented, only 10 provide information on how EI targets

309 were determined. However, some studies used methods to prescribe the EI that could result in
310 low EA. This included the use of habitual intake (Lynch et al., 2000) as both the suitability of
311 habitual intake or the method used to assess it from self-reports are potentially erroneous, or the
312 failure to account for EEE when using the principle of EA (Vargas-Molina et al., 2020, 2021) to
313 prescribe EI. We also note that in some studies, dietary interventions were not isoenergetic
314 (O’Keeffe et al., 1989), which may have confounded results.

315 *Moderate versus High Carbohydrate Diets*

316 The scaling of CHO intake to body mass in 2004 was one of the first practical attempts to
317 account for body mass differences in CHO recommendations, and indirectly addresses sex-based
318 differences given the typically smaller body size of women compared to men (Burke et al.,
319 2004). Yet, this may not adequately account for sex differences in substrate oxidation (Devries,
320 2016) and skeletal mass quantity and composition; on average women have more Type I
321 oxidative fibers than men (Haizlip et al., 2015; Wells, 2007). Despite a biological rationale for
322 differences in the daily CHO needs of male and female athletes, we were unable to locate a
323 single study with a MvF design that could directly investigate this issue. Two studies with
324 female-only cyclist cohorts compared the effects of a MvH diet on time to fatigue. Both of which
325 found an insignificant numerical difference in time to exhaustion between dietary interventions
326 (Dolins et al., 2003; O’Keeffe et al., 1989). While this may suggest that female athletes do not
327 benefit from higher CHO intake, such evidence is limited by the low caliber of athletes (Tier 1;
328 Recreationally Active and Tier 2; Trained/Developmental) with a low training volumes (~70
329 miles of cycling over 7 days (O’Keeffe et al., 1989) and ~100 miles of cycling over 6 days
330 (Dolins et al., 2003)) that may have been successfully fuelled by the moderate CHO diet. Given
331 that dietary surveys of female athletes report daily CHO intakes that are lower than their male

332 counterparts (Burke et al., 2001), often secondary to apparently lower EI, investigation of
333 whether higher CHO intakes are truly performance enhancing is needed.

334 *Low Carbohydrate, High Fat Diets*

335 Within our audit, six studies with a female-specific design examined changes in performance
336 associated with LCHF diets. Outcomes due to the LCHF diets in women included performance
337 decrements (Durkalec-Michalski et al., 2021; O’Keeffe et al., 1989; Sjödin et al., 2020), no
338 differences in performance (Durkalec-Michalski et al., 2021; Lynch et al., 2000), and
339 improvements in select strength parameters ($n = 1$; Sawyer et al., 2013). Limitations to this
340 research include the low caliber of athletes involved and poor methodological control of ovarian
341 hormones, with only 0.5 a study providing evidence of sufficient methodological control of
342 ovarian hormones. Overall, LCHF diets do not seem to provide performance benefits in
343 competitive male endurance athletes, either (Burke, 2021). In male athletes, there is evidence to
344 suggest that this may be due to decreased pyruvate dehydrogenase activation (Stellingwerff et
345 al., 2006). Further research is needed to examine sex-differences in response to a LCHF diet,
346 including if performance decrements occur through similar mechanisms of reduced economy of
347 higher-intensity exercise with greater oxygen cost of ATP production via fat oxidation.

348 *Periodized Carbohydrate Availability*

349 Only one study of P-CHO with a female-specific design was identified in this audit. This study
350 examined a 4-week program involving 5 days/week of fasted or acutely fed training in untrained
351 men and women (Stannard et al., 2010). Although maximal aerobic capacity increased by 9.7%
352 with fasted training compared to 2.5% with fed training ($p = 0.015$), without evidence of sex-
353 differences, men showed greater adaptations in muscle metabolism in the fasted condition, with a

354 reverse outcome in the fed condition for women (Stannard et al., 2010). This is an interesting
355 finding given that fasted training is an example of exercising in a state of both low EA and low
356 CHO availability, with evidence that women are more negatively affected by periods of low EA
357 than males (Koehler et al., 2016; Papageorgiou et al., 2017) and the outcomes of low EA and low
358 CHO availability may share overlap (Areta et al., 2021). As research into various aspects of P-
359 CHO is still in its infancy, it is important to include women in future studies to ensure that the
360 evolving guidelines can be applied to both male and female athletic populations.

361 **Conclusion**

362 Like other audited areas, women are under-represented in studies examining different approaches
363 to CHO in the everyday training diet, and the available research is limited by poor
364 methodological design in the control of ovarian hormones, and the implementation and
365 verification of chronic dietary interventions. Future research on CHO support for training should
366 use Best Practice Guidelines for the conduct and reporting of these aspects of research. Specific
367 studies of female athletes, including direct investigation of potential sex differences in response
368 to manipulation of CHO support for training, when corrected and normalized for fat free mass
369 compared to males, are needed to develop evidence-based guidelines that cover the whole of the
370 athletic population.

371 **Authorship:** L.M. Burke, M.A. Kuikman, A.K.A. McKay, and E.S. Smith formulated the
372 concept. M.A. Kuikman and E.S. Smith screened articles, classified papers, and extracted study
373 data. M.A. Kuikman wrote the manuscript with input from E.S. Smith, A.K.A. McKay, K.E.
374 Ackerman, R. Harris, K.J. Elliott-Sale, T. Stellingwerff, and Burke, L.M.

375 Conflict of interest:

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378 **Conflict of interest:** The authors declare no conflict of interest

For Peer Review

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Table 1 Classification of different research interests regarding chronic strategies around CHO support for training

Strategy (Burke et al., 2011; Burke et al., 2018)	Study Features
Moderate versus high carbohydrate (MvH)	Investigates chronic CHO intakes (>3 days in duration) Manipulates the type or amount of daily CHO intake to compare “habitual” intakes to strategies promoting greater daily muscle glycogen storage/restoration
Periodization of carbohydrate availability (P-CHO)	Investigates the integration of acute strategies of “train low” and “recover low” (manipulation of low CHO availability around training session) within program otherwise providing CHO-supported training May include manipulations of dietary CHO intake and timing/sequences of training sessions to achieve low CHO availability Includes investigation of acute response to “train low” sessions as well as chronic training studies
Low carbohydrate, high fat diets (LCHF)	Investigates sustained responses (>24 h) to low CHO intake Includes both ketogenic (<50 g/day CHO) and non-ketogenic (<3 g/kg BM CHO) approaches to LCHF Includes implementation of a period of CHO restoration following adaptation to chronic CHO restriction

Note: *CHO* carbohydrate; *BM* body mass

Figure 1: Flowchart demonstrating the screening process to identify papers examining chronic approaches to CHO support for training including the number of studies of the three different research interests

Figure 2: The total number of male and female participants (A) and total number of studies with at least one male or one female participant (B) for each of three different research interests for chronic approaches to CHO support for training

MvH moderate versus high; *LCHF* Low carbohydrate, high fat; *P-CHO* Periodisation of carbohydrate availability

Figure 3: Frequency of study design for each of three different research interests for chronic approaches to CHO support for training with the number of studies indicated within the legend (A) and the median number of male and female participants within each study design (B). *Significantly different median number of male versus female participants.

MvH moderate versus high; *LCHF* Low carbohydrate, high fat; *P-CHO* Periodisation of carbohydrate availability; *MvFdes* male versus female design; *MvFsub* male versus female sub-analysis.

Figure 4: Proportion of studies examining performance, health or indirect themes (A) and proportion of participants within each athlete tier: Tier 0 (Sedentary), Tier 1 (Recreationally Active), Tier 2 (Trained/Developmental), Tier 3 (Highly Trained/National), Tier 4 (Elite/International) and Tier 5 (World-Class) for each of the acute carbohydrate fuelling strategies (B).

MvH moderate versus high; *LCHF* Low carbohydrate, high fat; *P-CHO* Periodisation of carbohydrate availability

Figure 5: Histogram of yearly publication rate for male only studies and female only studies for all investigations of chronic approaches to CHO support for training

Figure 6: Proportion of studies classified as Gold standard (best practice methodologies followed), Silver/Bronze standard (some best practice methodologies followed), Ungraded (menstrual status defined but insufficient information on methodological control of ovarian hormonal profiles) and Unclassified (insufficient information to define menstrual status) for each of three different research interests for chronic approaches to CHO support for training. Number of studies within each menstrual classification indicated on legend.

MvH moderate versus high; *LCHF* Low carbohydrate, high fat; *P-CHO* Periodisation of carbohydrate availability

Figure 7: Method of dietary control, verification to ensure dietary adherence, and control of energy intake for studies with a female specific design. Energy intake control method was not considered for studies that allowed ad libitum intake or failed to provide information on methods to ensure dietary adherence. For studies that estimated total energy expenditure, energy intake divided by Harris-Benedict Equation and body mass presented as average and range in brackets.

TEE total energy expenditure; *BM* body mass; *EI* energy intake; *HBE* Harris-Benedict Equation.

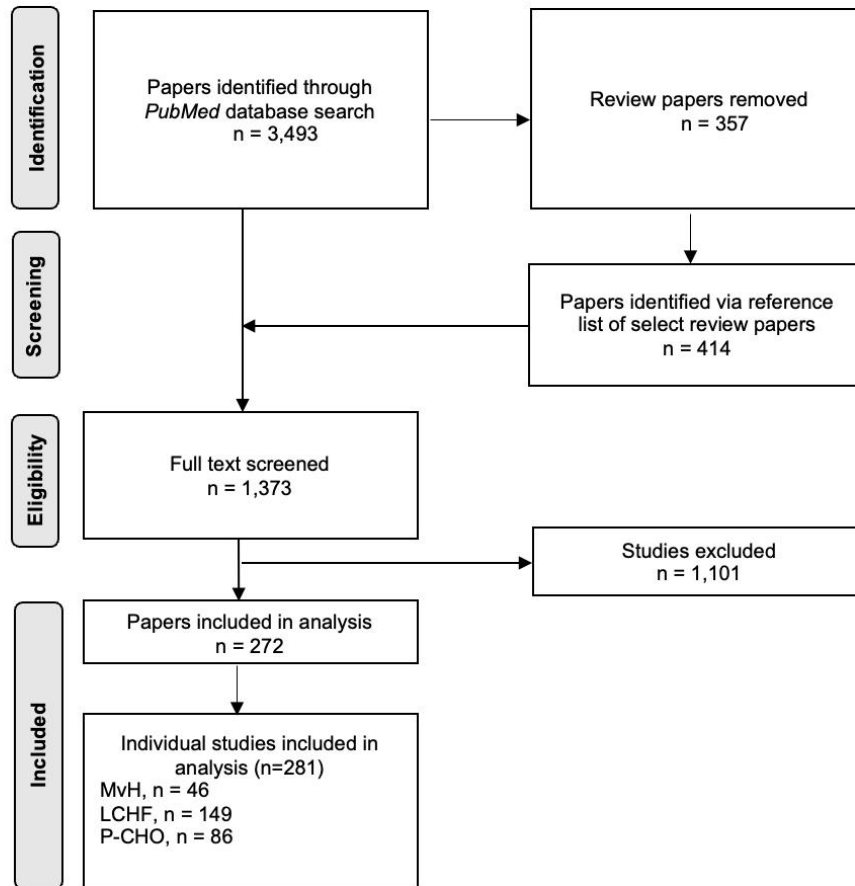


Figure 1: Flowchart demonstrating the screening process to identify papers examining chronic approaches to CHO support for training including the number of studies of the three different research interests.

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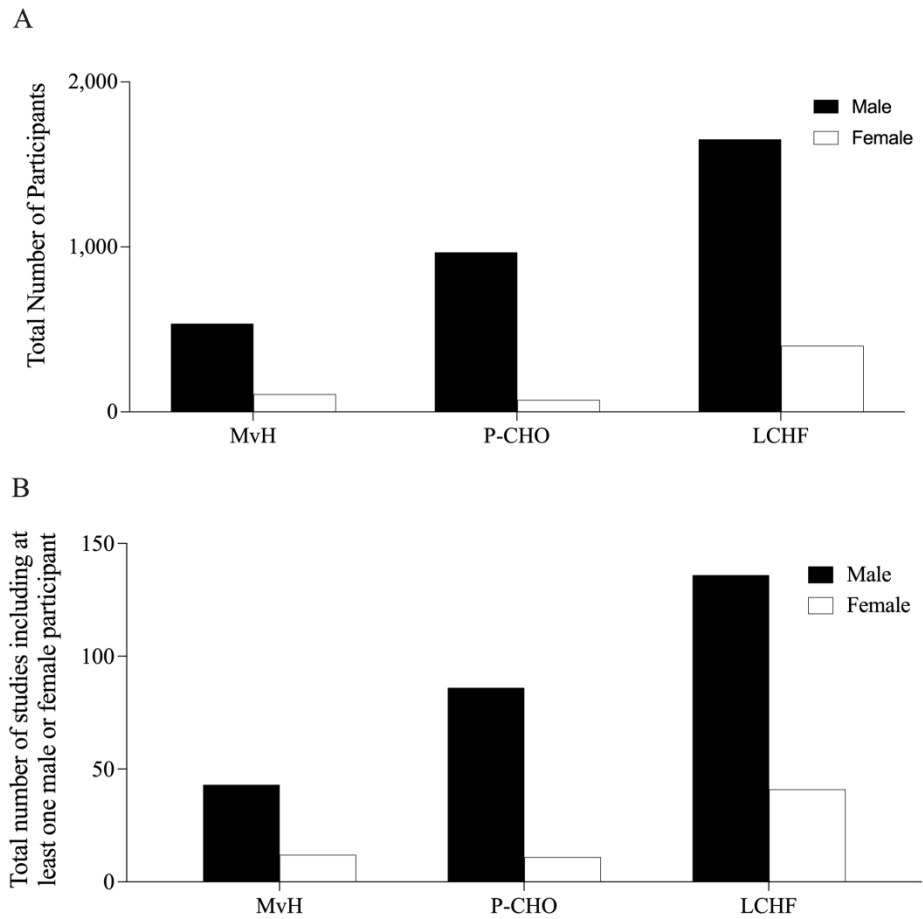


Figure 2: The total number of male and female participants (A) and total number of studies with at least one male or one female participant (B) for each of three different research interests for chronic approaches to CHO support for training. MvH Moderate versus high; LCHF Low carbohydrate, high fat; P-CHO Periodisation of carbohydrate availability.

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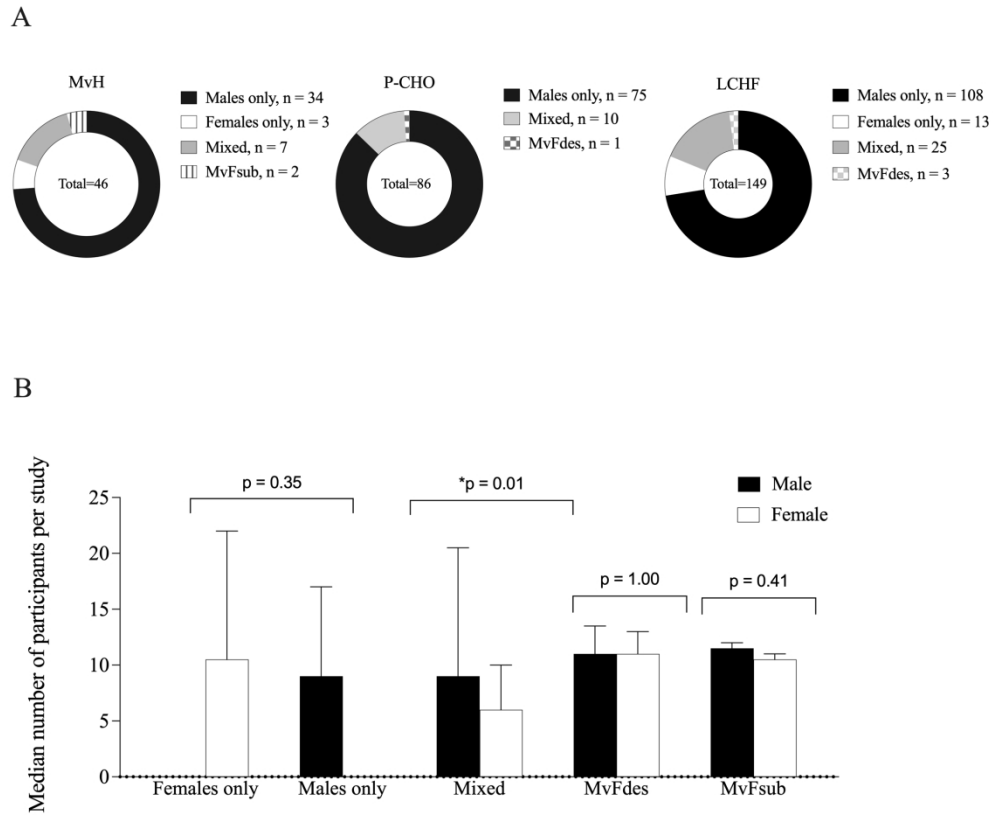


Figure 3: Frequency of study design for each of three different research interests for chronic approaches to CHO support for training with the number of studies indicated within the legend (A) and the median number of male and female participants within each study design (B). *Significantly different median number of male versus female participants. MvH moderate versus high; LCHF Low carbohydrate, high fat; P-CHO Periodisation of carbohydrate availability; MvFdes male versus female design; MvFsub male versus female sub-analysis.

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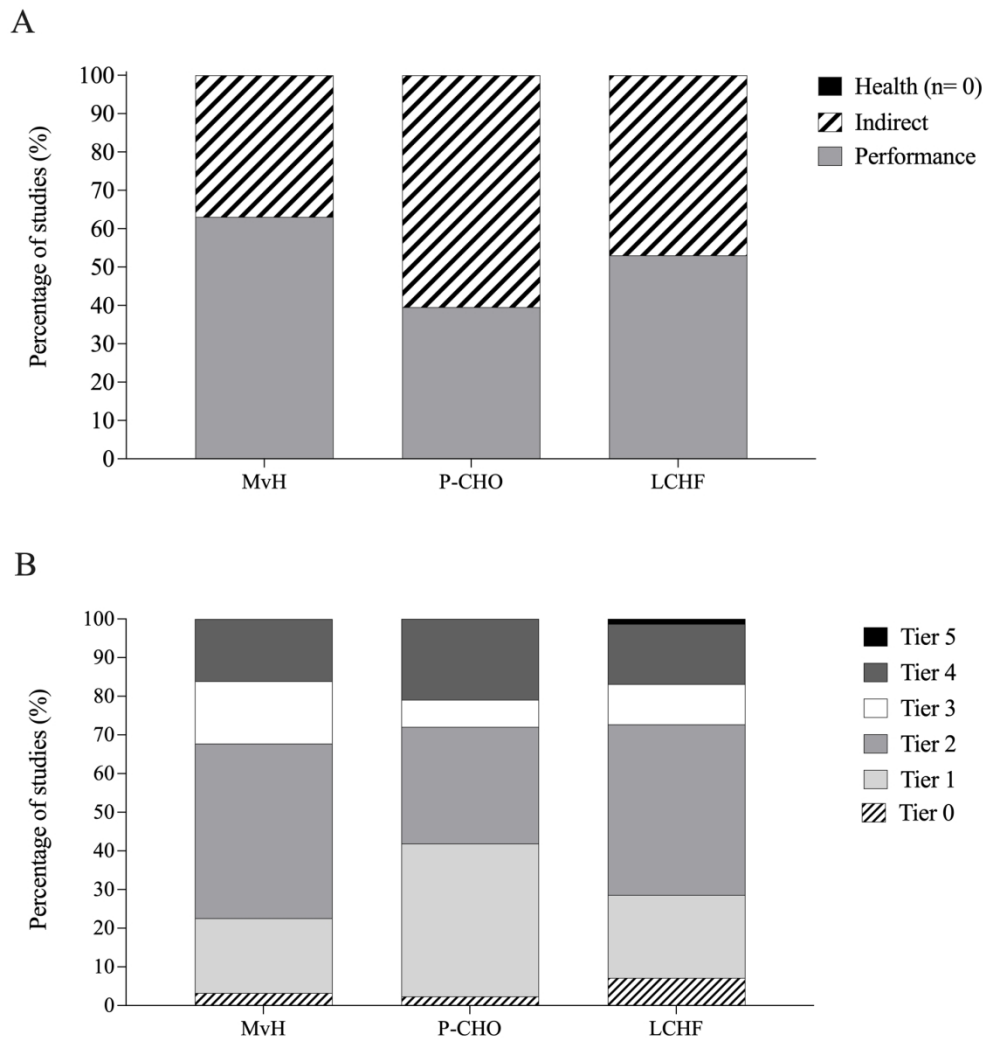


Figure 4: Proportion of studies examining performance, health or indirect themes (A) and proportion of participants within each athlete tier: Tier 0 (Sedentary), Tier 1 (Recreationally Active), Tier 2 (Trained/Developmental), Tier 3 (Highly Trained/National), Tier 4 (Elite/International) and Tier 5 (World-Class) for each of the acute carbohydrate fuelling strategies (B). MvH moderate versus high; LCHF Low carbohydrate, high fat; P-CHO Periodisation of carbohydrate availability.

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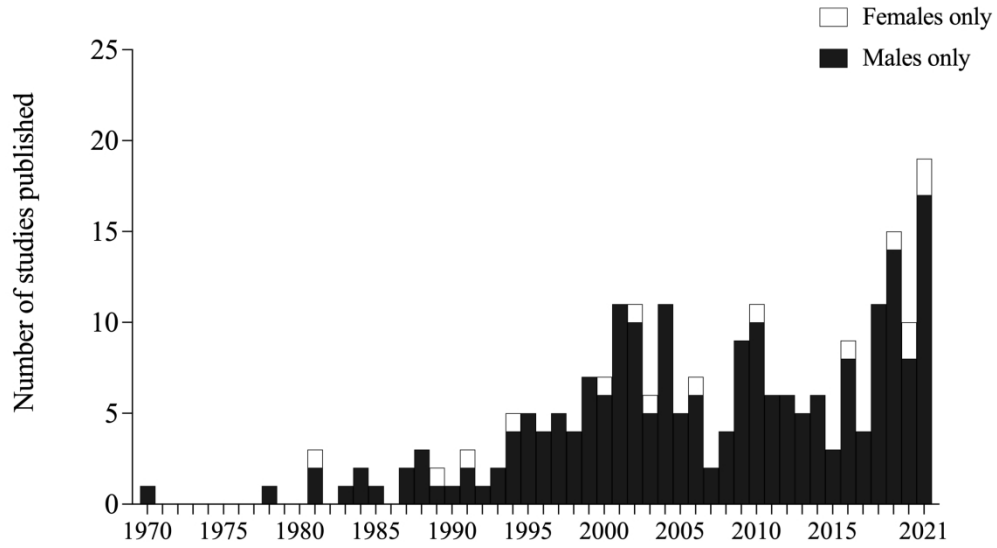


Figure 5: Histogram of yearly publication rate for male only studies and female only studies for all investigations of chronic approaches to CHO support for training.

198x109mm (300 x 300 DPI)

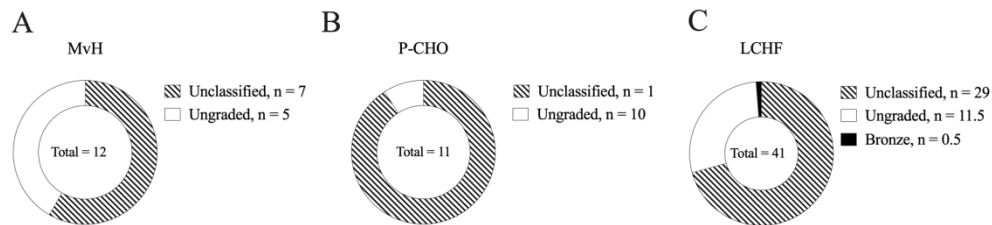


Figure 6: Proportion of studies classified as Gold standard (best practice methodologies followed), Silver/Bronze standard (some best practice methodologies followed), Ungraded (menstrual status defined but insufficient information on methodological control of ovarian hormonal profiles) and Unclassified (insufficient information to define menstrual status) for each of three different research interests for chronic approaches to CHO support for training. Number of studies within each menstrual classification indicated on legend. MvH moderate versus high; LCHF Low carbohydrate, high fat; P-CHO Periodisation of carbohydrate availability.

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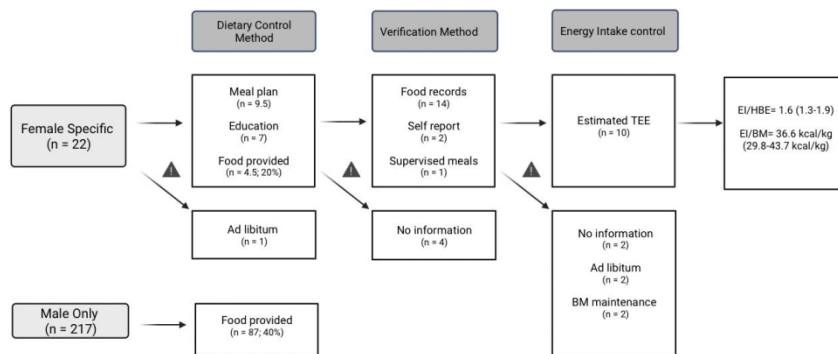


Figure 7: Method of dietary control, verification to ensure dietary adherence, and control of energy intake for studies with a female specific design. Energy intake control method was not considered for studies that allowed ad libitum intake or failed to provide information on methods to ensure dietary adherence. For studies that estimated total energy expenditure, energy intake divided by Harris-Benedict Equation and body mass presented as average and range in brackets. TEE total energy expenditure; BM body mass; EI energy intake; HBE Harris-Benedict Equation.

262x116mm (144 x 144 DPI)

TITLE	YEAR
Oral Glucose Ingestion Attenuates Exercise-Induced Activation of 50 -Amp-Activated Protein Kinase in Human Skeletal Muscle.	2006
Neither Beetroot Juice Supplementation Nor Increased Carbohydrate Oxidation Enhance Economy of Prolonged Exercise in Elite Race Walkers.	2021
Oral [13C]Glucose Oxidation During Prolonged Exercise After High- and Low-Carbohydrate Diets	1998
Carbohydrate Intake and Multiple Sprint Sports: With Special Reference to Football (Soccer).	1999
Regulation of Plasma Long-Chain Fatty Acid Oxidation in Relation to Uptake in Human Skeletal Muscle During Exercise.	2004
Effect of the Menstrual Cycle Phase and Diet on Blood Lactate Responss to Exercise	1994

Effects of Alterations in Dietary Carbohydrate Intake on Running Performance During a 10 Km Treadmill Time Trial.	1996
Effects of Moderate Dietary Manipulations on Swim Performance and on Blood Lactate-Swimming Velocity Curves.	1999
Human Skeletal Muscle Pyruvate Dehydrogenase Kinase Activity Increases After a Low-Carbohydrate Diet.	1998
High-Fat Diet Versus Habitual Diet Prior to Carbohydrate Loading: Effects of Exercise Metabolism and Cycling Performance.	2001
Regulation of Metabolic Genes in Human Skeletal Muscle by Short-Term Exercise and Diet Manipulation	2004
Carbohydrate Feeding During Recovery Alters the Skeletal Muscle Metabolic Response to Repeated Sessions of High-Intensity Interval Exercise in Humans.	2010
Carbohydrate Restriction Following Strenuous Glycogen-Depleting Exercise does not Potentiate the Acute Molecular Response Associated With Mitochondrial Biogenesis in Human Skeletal Muscle.	2021

Effect of the Intake of High Or Low Glycemic Index High Carbohydrate-Meals on Athletes' Sleep Quality in Pre-Game Nights.	2019
Overtraining Following Intensified Training With Normal Muscle Glycogen.	1995
Substrate Availability and Transcriptional Regulation of Metabolic Genes in Human Skeletal Muscle During Recovery From Exercise	2005
Dietary Carbohydrate Intake and Endurance Exercise Performance of Trained Female Cyclists	1989
Dietary Carbohydrate Intake and Endurance Exercise Performance of Trained Female Cyclists	1989
A 2 Week Cross-Over Intervention With a Low Carbohydrate, High Fat Diet Compared to a High Carbohydrate Diet Attenuates Exercise-Induced Cortisol Response, but not the Reduction of Exercise Capacity, in Recreational Athletes.	2021
A 3-Day High-Fat/Low-Carbohydrate Diet does not Alter Exercise-Induced Growth Hormone Response in Healthy Males.	2015

- A 3-Week, Low-Carbohydrate, High-Fat Diet Improves Multiple Serum Inflammatory Markers in Endurance-Trained Males. 2020
- A Low Carbohydrate Diet Affects Autonomic Modulation During Heavy but not Moderate Exercise. 2010
- A Low-Carbohydrate Ketogenic Diet Reduces Body Mass Without Compromising Performance in Powerlifting and Olympic Weightlifting Athletes. 2018
- A Short-Term Ketogenic Diet Impairs Markers of Bone Health in Response to Exercise. 2019
- A Short-Term, High-Fat Diet Up-Regulates Lipid Metabolism and Gene Expression in Human Skeletal Muscle. 2003
- Acute and Sustained Effects of a Periodized Carbohydrate Intake Using the Sleep-Low Model in Endurance-Trained Males 2019
- Acute Carbohydrate Ingestion does not Influence the Post-Exercise Iron-Regulatory Response in Elite Keto-Adapted Race Walkers. 2019

Acute Dietary Carbohydrate Manipulation and the Subsequent Inflammatory and Hepcidin Responses to Exercise.	2015
Acute Ketogenic Diet and Ketone Ester Supplementation Impairs Race Walk Performance.	2021
Adaptation to a Ketogenic Diet Modulates Adaptive and Mucosal Immune Markers in Trained Male Endurance Athletes.	2021
Adaptation to a Low Carbohydrate High Fat Diet Is Rapid but Impairs Endurance Exercise Metabolism and Performance Despite Enhanced Glycogen Availability.	2021
Adaptations to Short-Term High-Fat Diet Persist During Exercise Despite High Carbohydrate Availability.	2002
Adaptations to Skeletal Muscle With Endurance Exercise Training in the Acutely Fed Versus Overnight-Fasted State.	2010
Alterations in Dietary Carbohydrate, Protein, and Fat Intake and Mood State in Trained Female Cyclists.	1991

- Anaerobic Performance After a Low-Carbohydrate Diet (Lcd) Followed by 7 Days of Carbohydrate Loading in Male Basketball Players. 2019
- Analysis of the Effects of Dietary Pattern on the Oral Microbiome of Elite Endurance Athletes. 2019
- Autonomic and Perceptual Responses to Induction of a Ketogenic Diet in Free-Living Endurance Athletes: a Randomized, Crossover Trial. 2021
- Beneficial Metabolic Adaptations Due to Endurance Exercise Training in the Fasted State. 2011
- Case Study: Long-Term Low Carbohydrate, High Fat Diet Impairs Performance and Subjective Wellbeing in a World-Class Vegetarian Long-Distance Triathlete. 2018
- Case Study: Nutrition and Training Periodization in Three Elite Marathon Runners. 2012
- Changes in Body Composition and Substrate Utilization After a Short-Term Ketogenic Diet in Endurance-Trained Males. 2021

Changes in Metabolism but not Myocellular Signaling by Training With Cho-Restriction in Endurance Athletes.	2018
Changes in Metabolism but not Myocellular Signaling by Training With Cho-Restriction in Endurance Athletes.	2018
Chronic Adherence to a Ketogenic Diet Modifies Iron Metabolism in Elite Athletes.	2019
Chronic Ketogenic Low Carbohydrate High Fat Diet Has Minimal Effects on Acid-Base Status in Elite Athletes.	2018
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JOURNAL	AUTHORS
Biochemical and Biophysical Research Communications	Akerstrom TC and Birk JB and Klein DK and Erikstrup C and Plomgaard P and Pedersen BK and Wojtaszewski J
Nutrients	Burke LM and Hall R and Heikura IA and Ross ML and Tee N and Kent GL and Whitfield J and Forbes SF and Sharma AP and Jones AM and Peeling P and Blackwell JR and Mujika I and Mackay K and Kozior M and Vallance B and McKay AKA
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Klapcinska B and Sadowska-Krepa E and
Manowska B and Pilis W and Sobczak a
and Danch A

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Metabolism

Lima-Silva AE and Pires FO and Bertuzzi R
and Silva-Cavalcante MD and Oliveira RS
and Kiss MA and Bishop D

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Duhamel TA and Green HJ and Perco JG
and Ouyang J

Metabolism

Margolis LM and Wilson MA
and Whitney CC and Carrigan CT and
Murphy NE and Hatch AM and Montain
SJ and Pasiakos SM

Experimental Physiology

Hearris MA and Owens DJ and Strauss JA
and Shepherd SO and Sharples AP and
Morton JP and Louis JB

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Creer a and Gallagher P and Slivka D and
Jemiolo B and Fink W and Trappe S

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Hargreaves M and McConell G and
Proietto J

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Sports Nutrition

Margolis LM and Wilson MA and
Whitney CC and Carrigan CT and Murphy
NE and Hatch-McChesney a and Pasiakos
SM

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Johnson NA and Stannard SR and
Mehalski K and Trenell MI and
Sachinwalla T and Thompson CH and
Thompson MW

Psychophysiology
Lima-Silva AE and Pires FO and Bertuzzi
RC and Lira FS and Casarini D and Kiss
MA

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Endocrinology and Metabolism
Zderic TW and Schenk S and Davidson CJ
and Byerley LO and Coyle EF

Sports (Basel, Switzerland)
Kephart WC and Pledge CD and
Roberson PA and Mumford PW and
Romero MA and Mobley CB and Martin
JS and Young KC and Lowery RP and
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Physiology
Lindinger MI and Spriet LL and Hultman E
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and Richards EE and Gleeson M

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J Watt, Sean
L McGee, Stanley Chan, Mark Hargreaves
, Mark A Febbraio, David Stapleton,
and Bruce E Kemp

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Travlos AK and Zorzou AE and Gissis IT
and Papadopoulos CN and Sotiropoulos
AA

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and Occupational Physiology

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Maughan RJ

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O'Brien L and Collins K and Webb R and
Davies I and Doran D and
Amirabdollahian F

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and Maughan RJ

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and Hargreaves M and Febbraio MA

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and Kerr CG and Fink WJ and Costill DL

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Psilander N and Frank P and Flockhart M
and Sahlin K

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Hearris MA and Hammond KM and
Seaborne RA and Stocks B and Shepherd
SO and Philp A and Sharples AP and
Morton JP and Louis JB

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Podlogar T and Free B and Wallis GA

Medicine and Science in Sports and
Exercise

Gillen JB and West DWD and Williamson
EP and Fung HJW and Moore DR

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Endocrinology and Metabolism

Roepstorff C and Halberg N and Hillig T
and Saha AK and Ruderman NB and
Wojtaszewski JF and Richter EA and
Kiens B

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Waterworth SP and Spencer CC and
Porter AL and Morton JP

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and Tang J and Shepherd SO and Strauss
JA and Close GL and Cocks M and Louis J
and Pugh J and Stewart C and Sharples
AP and Morton JP

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and Green KA and Hardie DG and
Wojtaszewski JF and Richter EA and
Kiens B

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Lichtenbelt WD and Saris WH and
Westerterp KR

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Nutrition

Paris HL and Fulton TJ and Wilhite DP
and Baranaukas MN and Chapman RF
and Mickleborough TD

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Greenhaff PL

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a and Porter J and Burke LM and Costa
RJS

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and Smith JA

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MA and MacLaren DP and Macdonald IA
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PW and Collins SM and Matthews TD
and Gregory SM and Paolone WJ

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- Journal of Applied Physiology Camera DM and West DWD and Burd NA and Phillips SM and Garnham AP and Hawley JA and Coffey VG
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- Frontiers in Nutrition Cipryan L and Dostal T and Litschmannova M and Hofmann P and Maffetone PB and Laursen PB
- European Journal of Applied Physiology Johnson NA and Stannard SR and Chapman PG and Thompson MW
- Plos One Bennett S and Tiollier E and Brocherie F and Owens DJ and Morton JP and Louis J

European Journal of Sport Science

Salokannel MM and Hakulien OM and
Ahtianen JP

European Journal of Sport Science

Salokannel MM and Hakulien OM and
Ahtianen JP

For Peer Review

CHO STRATEGY

THEME

P-CHO

Indirect Associations

MvH

Indirect Associations

LCHF

Indirect Associations

MvH

Performance

P-CHO

Indirect Associations

MvH

Indirect Associations

For Peer Review

MvH Performance

LCHF Performance

LCHF Indirect Associations

LCHF Performance

P-CHO Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

For Peer Review

MvH Indirect Associations

MvH Performance

P-CHO Indirect Associations

LCHF Performance

MvH Performance

LCHF Performance

LCHF Indirect Associations

For Peer Review

LCHF Indirect Associations

P-CHO Performance

LCHF Performance

LCHF Indirect Associations

LCHF Indirect Associations

P-CHO Performance

LCHF Indirect Associations

For Peer Review

P-CHO Indirect Associations

LCHF Performance

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LCHF Performance

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LCHF Indirect Associations

For Peer Review

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For Peer Review

P-CHO Indirect Associations

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LCHF Indirect Associations

P-CHO Indirect Associations

LCHF Indirect Associations

P-CHO Performance

For Peer Review

LCHF Performance

LCHF Performance

LCHF Performance

LCHF Indirect Associations

MvH Performance

MvH Performance

MvH Performance

For Peer Review

LCHF Performance

LCHF Performance

LCHF Performance

LCHF Indirect Associations

LCHF Performance

LCHF Indirect Associations

MvH Performance

For Peer Review

LCHF Performance

LCHF Indirect Associations

LCHF Indirect Associations

P-CHO Performance

LCHF Indirect Associations

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P-CHO Performance

For Peer Review

MvH Performance

MvH Performance

LCHF Performance

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MvH Indirect Associations

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For Peer Review

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MvH Indirect Associations

MvH Performance

MvH Performance

For Peer Review

MvH Performance

MvH Performance

LCHF Performance

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LCHF Performance

LCHF Indirect Associations

LCHF Performance

For Peer Review

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MvH Performance

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MvH Indirect Associations

P-CHO Indirect Associations

MvH Performance

LCHF Performance

For Peer Review

LCHF Indirect Associations

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P-CHO Performance

MvH Performance

P-CHO Indirect Associations

For Peer Review

LCHF Performance

LCHF Indirect Associations

MvH Indirect Associations

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MvH Indirect Associations

P-CHO Performance

LCHF Indirect Associations

For Peer Review

LCHF Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

LCHF Performance

LCHF Performance

LCHF Indirect Associations

MvH Performance

For Peer Review

LCHF Indirect Associations

LCHF Performance

LCHF Indirect Associations

P-CHO Performance

LCHF Indirect Associations

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For Peer Review

LCHF Performance

P-CHO Performance

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MvH Performance

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For Peer Review

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MvH Indirect Associations

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MvH Performance

P-CHO Indirect Associations

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For Peer Review

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LCHF Performance

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LCHF Performance

MvH Indirect Associations

P-CHO Performance

LCHF Performance

For Peer Review

LCHF Indirect Associations

LCHF indirect Associations

LCHF Performance

MvH Indirect Associations

P-CHO Performance

LCHF Indirect Associations

LCHF Performance

For Peer Review

LCHF	Performance
MvH	Indirect Associations
LCHF	Indirect Associations
LCHF	Performance
MvH	Performance
LCHF	Indirect Associations
LCHF	Indirect Associations

For Peer Review

P-CHO

Performance

LCHF

Indirect Associations

LCHF

Indirect Associations

P-CHO

Performance

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Indirect Associations

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Indirect Associations

LCHF

Performance

For Peer Review

LCHF	Performance
LCHF	Indirect Associations
MvH	Indirect Associations
P-CHO	Performance
P-CHO	Indirect Associations
LCHF	Indirect Associations
LCHF	Indirect Associations

For Peer Review

LCHF Indirect Associations

MvH Indirect Associations

LCHF Performance

LCHF Indirect Associations

LCHF Indirect Associations

P-CHO Indirect Associations

P-CHO Performance

For Peer Review

MvH Indirect Associations

LCHF Indirect Associations

LCHF Performance

LCHF Performance

MvH Performance

LCHF Indirect Associations

MvH Performance

For Peer Review

LCHF Indirect Associations

LCHF Indirect Associations

LCHF Performance

LCHF Performance

MvH Indirect Associations

LCHF Performance

MvH Performance

For Peer Review

MvH	Performance
P-CHO	Indirect Associations
LCHF	Indirect Associations
LCHF	Indirect Associations
LCHF	Performance
LCHF	Indirect Associations
P-CHO	Indirect Associations

For Peer Review

P-CHO	Performance
LCHF	Performance
MvH	Indirect Associations
LCHF	Performance
LCHF	Indirect Associations
LCHF	Indirect Associations
P-CHO	Indirect Associations

For Peer Review

P-CHO

Performance

P-CHO

Performance

P-CHO

Performance

P-CHO

Indirect Associations

P-CHO

Indirect Associations

LCHF

Indirect Associations

LCHF

Indirect Associations

For Peer Review

P-CHO Indirect Associations

LCHF Indirect Associations

LCHF Indirect Associations

LCHF Performance

LCHF Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

For Peer Review

P-CHO Performance

P-CHO Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

LCHF Indirect Associations

For Peer Review

LCHF Performance

LCHF Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

For Peer Review

P-CHO Indirect Associations

LCHF Performance

P-CHO Indirect Associations

LCHF Performance

P-CHO Indirect Associations

P-CHO Indirect Associations

P-CHO Indirect Associations

For Peer Review

P-CHO Indirect Associations

P-CHO Performance

LCHF Performance

MvH Performance

LCHF Indirect Associations

MvH Performance

LCHF Indirect Associations

For Peer Review

P-CHO Performance

P-CHO Indirect Associations

LCHF Performance

P-CHO Indirect Associations

P-CHO Performance

P-CHO Performance

P-CHO Indirect Associations

For Peer Review

P-CHO Indirect Associations

P-CHO Performance

P-CHO Indirect Associations

P-CHO Indirect Associations

LCHF Indirect Associations

P-CHO Performance

LCHF Performance

For Peer Review

P-CHO Performance

P-CHO Performance

P-CHO Performance

LCHF Indirect Associations

LCHF Performance

MvH Performance

LCHF Performance

For Peer Review

LCHF Performance

P-CHO Indirect Associations

LCHF Indirect Associations

LCHF Indirect Associations

LCHF Performance

LCHF Performance

P-CHO Performance

For Peer Review

P-CHO

Indirect Associations

P-CHO

Performance

For Peer Review

POPULATION	ATHLETIC CALIBRE
Males Only	Unclassified
Males Only	Tier 4
Males Only	Unclassified
Males Only	Unclassified
Males Only	Tier 1
Females Only	Unclassified

Males Only	Unclassified
Mixed cohort	Tier 2
Mixed cohort	Tier 0
Males Only	Unclassified
Males Only	Unclassified
Males Only	Tier 1
Males Only	Tier 1

For Peer Review

Males Only

Tier 2

Males Only

Tier 2

Males Only

Unclassified

Females Only

Tier 2

Females Only

Tier 2

Males Only

Tier 2

Males Only

Unclassified

For Peer Review

Males Only

Tier 2

Males Only

Unclassified

Mixed cohort

Tier 3

Mixed cohort

Tier 4

Males Only

Unclassified

Males Only

Tier 1

Mixed cohort

Tier 4

For Peer Review

Males Only Tier 2

Mixed cohort Tier 4

Males Only Tier 2

Males Only Tier 4

Males Only Unclassified

MvFdes Unclassified

Females Only Tier 2

Males Only Tier 3

Males Only Tier 4

Males Only Tier 2

Males Only Tier 1

Males Only Tier 5

Males Only Tier 4

Males Only Tier 2

For Peer Review

Males Only

Tier 4

Males Only

Unclassified

Mixed cohort

Tier 4

Mixed cohort

Tier 4

Mixed cohort

Tier 4

Males Only

Unclassified

Mixed cohort

Tier 4

For Peer Review

Mixed cohort	Tier 4
Males Only	Tier 2
Males Only	Unclassified
Males Only	Tier 1
Males Only	Tier 3
Males Only	Unclassified
Mixed cohort	Tier 3

For Peer Review

Males Only

Tier 0

Males Only

Unclassified

Males Only

Tier 2

MvFdes

Tier 2

Males Only

Tier 2

Females Only

Unclassified

Males Only

Tier 3

Males Only

Unclassified

Mixed cohort

Unclassified

Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

Mixed cohort

Tier 2

Males Only

Unclassified

For Peer Review

Females Only	Tier 1
Males Only	Tier 2
Mixed cohort	Tier 0
Males Only	Tier 1
Males Only	Tier 1
Males Only	Tier 4
Females Only	Unclassified

Females Only Unclassified

Females Only Unclassified

Males Only Tier 3

Males Only Tier 2

Males Only Unclassified

Males Only Tier 4

Males Only Tier 4

For Peer Review

Males Only Tier 2

Males Only Tier 3

Males Only Tier 3

MvFsub Tier 2

Males Only Tier 4

Mixed cohort Tier 2

Males Only Tier 3

Males Only

Unclassified

Mixed cohort

Tier 2

Females Only

Unclassified

Males Only

Unclassified

Males Only

Tier 2

Mixed cohort

Unclassified

Males Only

Tier 2

For Peer Review

Males Only

Unclassified

Males Only

Unclassified

Males Only

Tier 3

Males Only

Tier 2

Males Only

Tier 2

Males Only

Tier 2

Males Only

Tier 3

For Peer Review

Males Only

Unclassified

Males Only

Unclassified

Males Only

Tier 0

Males Only

Unclassified

Mixed cohort

Tier 2

Males Only

Tier 2

Males Only

Tier 2

For Peer Review

Males Only

Unclassified

Males Only

Tier 1

Males Only

Unclassified

Males Only

Unclassified

Males Only

Tier 1

Mixed cohort

Tier 1

Mixed cohort

Unclassified

For Peer Review

Males Only

Unclassified

Males Only

Tier 0

Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

Females Only

Unclassified

For Peer Review

MvFdes	Tier 2
Males Only	Tier 2
Mixed cohort	Tier 2
Males Only	Tier 3
Males Only	Tier 1
Males Only	Tier 4
Males Only	Tier 4

Males Only

Tier 1

Mixed cohort

Unclassified

Males Only

Unclassified

Males Only

Tier 2

MvFsub

Tier 3

Males Only

Tier 4

Mixed cohort

Unclassified

Males Only

Tier 2

Males Only

Unclassified

Mixed cohort

Tier 2

Males Only

Tier 2

Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

For Peer Review

Males Only

Unclassified

Males Only

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Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

Males Only

Tier 2

Males Only

Unclassified

Females Only

Unclassified

Males Only

Unclassified

Males Only

Tier 1

Males Only

Tier 2

Males Only

Unclassified

Males Only

Unclassified

Males Only

Tier 3

For Peer Review

Males Only

Tier 4

Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

Mixed cohort

Tier 1

Males Only

Unclassified

Males Only

Tier 2

Males Only

Tier 1

Males Only

Unclassified

Males Only

Tier 2

Males Only

Tier 2

Males Only

Tier 2

Males Only

Tier 2

Males Only

Unclassified

For Peer Review

Males Only Unclassified

Males Only Tier 4

Males Only Tier 2

Males Only Tier 2

Males Only Unclassified

Mixed cohort Tier 4

Mixed cohort Tier 4

Males Only

Tier 2

Males Only

Tier 1

Males Only

Tier 2

Males Only

Unclassified

Males Only

Unclassified

Males Only

Comparison study- tier 1 (n=11) vs tier 0 (n=6)

Males Only

Unclassified

For Peer Review

Males Only

Tier 1

Males Only

Tier 2

Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

Females Only

Tier 1

Males Only

Unclassified

Males Only

Tier 1

Males Only

Unclassified

Males Only

Tier 1

Males Only

Unclassified

Males Only

Tier 2

Males Only

Tier 1

Males Only

Unclassified

For Peer Review

Males Only

Tier 2

Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

Males Only

Tier 1

Males Only

Unclassified

Females Only

Unclassified

For Peer Review

Males Only

Unclassified

Females Only

Tier 0

Males Only

Unclassified

Males Only

Tier 2

Males Only

Unclassified

Males Only

Unclassified

Males Only

Unclassified

For Peer Review

Males Only	Tier 1
Mixed cohort	Unclassified
Males Only	Tier 3
Males Only	Unclassified
Males Only	Unclassified
Males Only	Tier 2
Males Only	Unclassified

For Peer Review

Males Only Unclassified

Males Only Unclassified

Males Only Unclassified

Males Only Tier 3

Males Only Unclassified

Mixed cohort Tier 1

Males Only Tier 1

For Peer Review

Males Only	Tier 1
Males Only	Tier 1
Males Only	Unclassified
Males Only	Tier 1
Mixed cohort	Tier 0
Males Only	Unclassified
Males Only	Unclassified

For Peer Review

Males Only Tier 2

Males Only Tier 2

Males Only Tier 4

Males Only Unclassified

Mixed cohort Unclassified

Males Only Tier 1

MvFdes Tier 1

Males Only

Tier 1

Males Only

Tier 1

Females Only

Unclassified

Males Only

Tier 4

Mixed cohort

Unclassified

Males Only

Unclassified

Mixed cohort

Tier 2

For Peer Review

Mixed cohort

Unclassified

Mixed cohort

Unclassified

For Peer Review

MENSTRUAL STATUS

Menstrual Grade

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

MC

Ungraded

For Peer Review

N/A

N/A

Unclassified

N/A

Unclassified

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

N/A

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N/A

MC

Ungraded

MC

Ungraded

N/A

N/A

N/A

N/A

For Peer Review

N/A

N/A

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N/A

Unclassified

N/A

Unclassified

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Unclassified

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MC

Ungraded

For Peer Review

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For Peer Review

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For Peer Review

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Mixed

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For Peer Review

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MC Ungraded

For Peer Review

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For Peer Review

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For Peer Review

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For Peer Review

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For Peer Review

Supplementary Table 1 Ranking system to assess studies with female participants as per the standardized protocol of Smith et al., 2022

Hormonal Contraceptive Studies				
Tier	MC studies	Oral contraceptive pill	Other	Menstrual irregularities studies
Gold	<p>Participants are eumenorrheic:</p> <ol style="list-style-type: none"> 1. have MC lengths ≥ 21 days and ≤ 35 days resulting in nine or more consecutive periods per year 2. evidence of LH surge 3. correct hormonal profile (from blood sample analysis) 4. no HC use 3 months prior to recruitment <p>MC characteristics are tracked for ≥ 2 months prior to testing</p>	<p>OCP use ≥ 3 months prior to recruitment (i.e., length of usage), with the type (e.g., mono, bi, or triphasic; combined or progesterone only and formulation [name and concentration of exogenous hormones]) stated</p> <p>Stipulate and consider OCP taking (i.e., active OCP) days and OCP free (i.e., inactive/placebo OCP) days</p> <p>One brand/type of OCP per group of participants</p>	<p>HC use ≥ 3 months prior to recruitment (i.e., length of usage), with the type (e.g., implants, injections, intrauterine devices/coils that are hormone releasing and NOT copper-based, vaginal rings, contraceptive transdermal patches), and formulation (e.g., combined or progesterone only; names and concentration of exogenous hormones) stated</p> <p>One type of HC per group of participants</p>	<p>Condition diagnosed by medical professional as part of the study</p> <p>Length of condition stated</p>

Hormonal Contraceptive Studies

Tier	MC studies	Oral contraceptive pill	Other	Menstrual irregularities studies
Silver	<p>Outcome measures are repeated in a second cycle</p> <p>Participants are naturally menstruating with ovulatory cycles:</p> <ol style="list-style-type: none"> 1. they experience menstruation, with MC lengths ≥ 21 days and ≤ 35 days 2. confirmed ovulation (LH) but without correct hormonal profile 3. prior HC use not stated or less than 3 months prior to recruitment 	<p>Two of three stated: OCP length of usage, type, and formulation</p> <p>Do/do not stipulate and consider OCP-taking (i.e., active OCP) days and OCP-free (i.e., inactive/placebo OCP) days</p> <p>One or more than one brand/type of OCP per group of participants</p>	<p>Two of three stated: HC length of usage, type, and formulation</p> <p>One or more than one type of HC per group of participants</p>	<p>Condition diagnosed by medical professional not as part of the study—self-reported or via medical records</p> <p>Length of condition stated/not stated</p>

Hormonal Contraceptive Studies

Tier	MC studies	Oral contraceptive pill	Other	Menstrual irregularities studies
Bronze	<p>MC characteristics are tracked for 1 month prior to testing</p> <p>Outcome measures not repeated in a second cycle</p> <p>Participants are naturally menstruating:</p> <ol style="list-style-type: none"> 1. they experience menstruation, with MC lengths ≥ 21 days and ≤ 35 days 2. without confirmed ovulation and correct hormonal profile 3. prior HC use not stated or < 3 months prior to recruitment 	<p>One of three stated: OCP length of usage, type, and formulation</p> <p>Do not stipulate and consider OCP taking (i.e., active OCP) days and OCP free (i.e., inactive/placebo OCP) days</p> <p>More than one brand/type of OCP per group of participants</p>	<p>One of three stated: HC length of usage, type, formulation</p> <p>More than one type of HC per group of participants</p>	<p>Self-reported condition without medical diagnosis OR not specified if/how the condition was diagnosed</p> <p>Length of condition not stated</p>

Hormonal Contraceptive Studies

Tier	MC studies	Oral contraceptive pill	Other	Menstrual irregularities studies
Ungraded	<p>No tracking of MC characteristics prior to testing</p> <p>Insufficient detail to award a gold, silver, or bronze</p>	<p>Insufficient detail to award a gold, silver, or bronze</p>	<p>Insufficient detail to award a gold, silver, or bronze</p>	<p>Insufficient detail to award a gold, silver, or bronze</p>

Note. HC = hormonal contraception; LH = luteinizing hormone; MC = menstrual cycle; OCP = oral contraceptive pill.