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1 **Is exercise best served on an empty stomach?**

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10

11 Short title: Exercise and timing of food intake

12 Keywords: physical activity, nutrient timing, metabolism, health

13 **Abstract.**

14 The objective of this review paper is to evaluate the impact of undertaking aerobic exercise in the
15 overnight-fasted versus fed-state, in the context of optimising the health or therapeutic benefits of
16 regular physical activity. Conducting a single bout of aerobic exercise in the overnight-fasted versus
17 fed-state can differentially modulate aspects of metabolism and energy balance behaviours. This
18 includes, but is not limited to, increased utilisation of fat as a fuel source, improved plasma lipid
19 profiles, enhanced activation of molecular signalling pathways related to fuel metabolism in skeletal
20 muscle and adipose tissue, and reductions in energy intake over the course of a day. The impact of a
21 single bout of overnight-fasted versus fed-state exercise on short-term glycaemic control is variable,
22 being affected by the experimental conditions, the time-frame of measurement and possibly the
23 subject population studied. The health or therapeutic response to undertaking overnight-fasted versus
24 fed-state exercise for a sustained period of time in the form of exercise training is less clear, due to a
25 limited number of studies. From the extant literature, there is evidence that overnight-fasted exercise
26 in young, healthy men can enhance training-induced adaptations in skeletal muscle metabolic profile,
27 and mitigate against the negative consequences of short-term excess energy intake on glucose
28 tolerance compared to exercising in the fed-state. Nonetheless, further long-term studies are required,
29 particularly in populations at-risk or living with cardio-metabolic disease to elucidate if feeding status
30 prior to exercise modulates metabolism or energy balance behaviours to an extent that could impact
31 upon the health or therapeutic benefits of exercise.

32 **Introduction.**

33 Regular physical activity and exercise has been associated with a number of health benefits including
34 reduced risk of developing coronary heart disease, stroke, type 2 diabetes and some forms of cancer.
35 Mechanistically, these effects are mediated through improvements in numerous risk factors for
36 disease such as blood pressure, lipoprotein profile, inflammation, insulin sensitivity and weight
37 management (1). Regular physical activity and exercise has also been increasingly recognised for its
38 therapeutic potential in many clinical contexts such as obesity, type 2 diabetes and cardiovascular
39 disease (2, 3). Indeed, the concept of exercise as medicine has gained significant traction in recent
40 years with initiatives such as Exercise is Medicine® (<http://www.exerciseismedicine.org/>) managed
41 by the American College of Sports Medicine established to increase the use of exercise programs
42 within primary and other health care settings. A parallel exists between the salutary effects of exercise
43 and the clinical effectiveness of many other ‘medications’ in that some individuals display a less than
44 expected therapeutic response. For example, the HERITAGE Family Study showed that structured
45 regular aerobic exercise training led to increased insulin sensitivity (determined by intravenous
46 glucose tolerance test) *on average* in previously sedentary individuals. However, of the entire cohort,
47 42% of participants displayed no change or decreased insulin sensitivity (4). A further study reported
48 that 12-weeks structured aerobic exercise training resulted in weight-loss of ~4kg *on average*,
49 although over 50% of participants were identified as losing less weight than predicted (5). Whether
50 such observations reflect true inter-individual variability in responsiveness to exercise training is
51 debated, but the evidence does indicate that some individuals may not be achieving the full potential
52 benefits of exercise. Physical activity relates to any type of movement that requires muscle
53 contraction and raises energy expenditure, a sub-component of which is structured, volitional
54 exercise. While generic physical activity and exercise guidelines are clearly established, identifying
55 strategies to maximise the therapeutic benefit for all individuals represents an important step in the
56 refinement and optimisation of public health physical activity recommendations.

57 Sport and exercise scientists have been studying nutrient-exercise interactions for decades in the
58 search for nutritional strategies that may contribute to improving exercise performance. It is well
59 known that nutrient intake around exercise can interact with, and modulate, metabolic, hormonal and
60 molecular responses that may ultimately influence exercise adaptation in endurance-trained
61 individuals (6). While ensuring a high dietary carbohydrate intake remains critical for optimising
62 acute endurance exercise performance and recovery, such a strategy has been proposed to blunt some
63 of the key skeletal muscle adaptive responses to exercise training (7). Accordingly, endurance athletes
64 are now advised to consider a periodised dietary approach by altering nutrient - and particularly
65 carbohydrate intake - as appropriate to support their training and performance goals (8). This may

66 include undertaking selected training sessions under conditions of low carbohydrate availability in
67 order to maximise the adaptive response to exercise, such as performing exercise in the overnight-
68 fasted versus postprandial state. Much of the nutrient-exercise interaction research has occurred in
69 the sports performance domain, but there is increasing interest in exploring its potential translation
70 into optimising exercise responses for health or therapeutic benefit (9, 10). It is well-known that the
71 effectiveness of some medicines may be reduced by the presence of nutrients in the gastro-intestinal
72 tract or the direct effects of nutrients on drug metabolism (11). An important question in light of
73 maximising the therapeutic benefit of exercise for all individuals is whether exercise, like some
74 medicines, is best taken on an empty stomach? Perhaps the less than expected response to exercise
75 training observed in some individuals relates to their feeding status around individual exercise bouts?
76 Accordingly, in this narrative review we evaluate the impact of undertaking aerobic exercise in the
77 overnight-fasted versus fed-state in the context of optimising the health or therapeutic benefits of
78 regular physical activity.

79

80 **Short-term metabolic responses to overnight-fasted versus fed-state exercise**

81 Energy production during sustained aerobic exercise performed in the overnight-fasted state (i.e., 8-
82 12 h) is supported primarily by the oxidation of endogenous fat and carbohydrate stores. Fat oxidation
83 predominates during low intensity exercise (<45% VO_2max), both fat and carbohydrate oxidation
84 increase to support moderate intensity exercise (45-65% VO_2max), while under most conditions
85 carbohydrate oxidation predominates at higher exercise intensities (>65% VO_2max). A recent
86 systematic review and meta-analysis clearly demonstrated that as compared to performing exercise
87 in the overnight fasted-state, the consumption of a carbohydrate-containing meal between 0.5-3 h
88 before exercise reduces fat oxidation (and increases carbohydrate oxidation) during exercise
89 performed for up to 2 h duration at <70% VO_2max (12). The suppression of fat oxidation during fed-
90 state exercise occurred regardless of exercise duration, participant sex, BMI, exercise training status,
91 duration between feeding and exercise or meal carbohydrate content. Plasma non-esterified fatty acid
92 (NEFA) concentrations did not significantly differ between exercise performed in the fed versus
93 overnight-fasted state. A clear effect of fed-state exercise on blood glucose and insulin concentrations
94 points towards increases in glycolytic flux as the dominant regulator of fuel metabolism in these
95 conditions (13). Further, previous research has established that the increased fat oxidation observed
96 during exercise in the overnight-fasted state appears to be supported by both increased plasma long-
97 chain fatty acid oxidation and Type 1 skeletal muscle fibre intramuscular triacylglycerol (IMTAG)

98 utilisation at least in lean individuals (13, 14). There does not appear to be any modulation of liver
99 fat during exercise regardless of whether this was performed in the overnight-fasted or fed state (15).

100 Whether the increased fat oxidation when exercise is performed in the overnight-fasted state can
101 impact upon daily fat oxidation, which would be more representative of long-term potential to alter
102 fat balance, is of paramount importance. Traditionally, despite exercise increasing fat oxidation
103 during the exercise bout itself, increases in fat oxidation and reductions in fat balance over a 24 h
104 period measured using whole room indirect calorimetry have not been observed when studied under
105 conditions of energy balance (16). This has been attributed to effects of insulin as a consequence of
106 consuming carbohydrate containing meals suppressing lipid utilisation throughout the day. However,
107 it is notable that exercise in these studies was not undertaken in the overnight-fasted state. Iyawama
108 and colleagues demonstrated recently in lean healthy men that 1 h of moderate intensity exercise
109 results in increased 24 h fat oxidation measured using whole-room indirect calorimetry when exercise
110 was performed before (i.e., in the overnight-fasted state) breakfast, but not after lunch or dinner, even
111 when participants remained in overall energy balance (17). The same group have also shown
112 improved 24 h fat oxidation and fat balance with pre-breakfast exercise in women (18). Exercise
113 performed in the overnight-fasted state would appear necessary to alter 24 h fat oxidation. While this
114 area has not received extensive mechanistic investigation, negative correlations between energy
115 balance or carbohydrate balance with 24 h fat oxidation suggests transient energy and/or
116 carbohydrate deficits may be driving the response (17).

117 The study of nutrient-exercise interactions in the context of substrate oxidation is important because
118 links between fat oxidation during exercise and daily fat oxidation have been made (19), as have
119 associations between daily fat oxidation and obesity risk (20). Of potentially equal importance is
120 consideration of how timing of food intake around exercise modulates other risk factors for cardio-
121 metabolic diseases, such as circulating lipid and glucose concentrations. In regards to blood lipid
122 profiles, a study by Enevoldsen and colleagues is insightful (21). This group determined blood
123 metabolite and hormone responses across the course of 5.5 h in young healthy men who undertook
124 exercise either before or after mixed macronutrient meal ingestion. Over the duration of the study
125 period, a more favourable response of circulating markers of lipid availability (e.g., lower plasma
126 triacylglycerol [TAG] and very low density lipoprotein-TAG [VLDL-TAG] concentrations) was
127 observed when exercise was performed before as compared after to meal ingestion. A similar result
128 was observed more recently in a study of overweight men, whereby exercise followed by food intake
129 but not food intake followed by exercise significantly lowered plasma TAG concentrations as
130 compared to a non-exercise control trial (22). Collectively, the aforementioned studies imply a

131 potentially beneficial impact of overnight-fasted versus fed-state exercise on aspects of body fat
132 regulation and lipid metabolism at least in the context of single bouts of exercise.

133 The impact of overnight-fasted versus fed-state exercise on aspects of glycaemic control has been
134 subject to considerable recent debate (23). Provision of carbohydrate containing meals increases
135 blood glucose and insulin concentrations, but when this is followed by exercise glucose uptake into
136 skeletal muscle is enhanced leading to a lowering effect on blood glucose. This has been argued to
137 be of particular importance in the context of diabetes, with the commencement of exercise 30-90 min
138 post-prandial suggested to be optimal in accelerating meal-derived glucose disposal thus avoiding
139 hyperglycaemia but also minimising risk of post-exercise hypoglycaemia (23). This glucose lowering
140 effect of fed-state exercise in type 2 diabetes does appear to be most pronounced in those with the
141 highest pre-exercise blood glucose concentrations (24). Taking subsequent meals into account can
142 present a different picture. For example, feeding prior to exercise in lean, healthy individuals has been
143 observed to increase the post-exercise postprandial glucose response to mixed macronutrient
144 ingestion as compared to fasted-state exercise (25). Furthermore, when glycaemic control was
145 assessed in individuals with prediabetes over the course of a full day after overnight-fasted or fed-
146 state exercise using continuous glucose monitoring (CGM), interstitial glucose variability but not
147 total interstitial glucose exposure (area under the curve, AUC) was improved with fed-state exercise
148 (26). It would seem that the reported influence of a single bout of overnight-fasted versus fed-state
149 exercise on short-term glycaemic control can be affected by the experimental conditions (e.g., when
150 assessed over single *versus* multiple meals), the time-frame of measurement and possibly the
151 populations studied. However, as will be discussed in a later section, it is critically important to
152 consider the difference between the acute effects of a single exercise bout and the adaptive response
153 to chronic exercise training resulting from the culmination of those single exercise bouts.

154

155 **Short-term energy balance behaviour responses to overnight-fasted versus fed-state exercise**

156 Exercising in the overnight-fasted versus fed-state will clearly lead to a longer period of energy
157 deficit, and from an energy balance perspective it is important to understand the extent to which
158 compensation of this energy deficit may occur during the post-exercise period.

159 This was initially investigated in a study by Gonzalez and colleagues who had 12 young physically
160 active men undertake 1 h moderate intensity treadmill running exercise performed in the overnight-
161 fasted state (FAST) or 2 h after breakfast consumption (FED) (27). After exercise, all participants
162 consumed a standardised mixed-macronutrient drink, followed 90 minutes later by provision of an

163 *ad libitum* test lunch, allowing for calculation of energy and macronutrient intake. Indirect
164 calorimetry was conducted during the experiment to calculate energy expenditure and substrate
165 oxidation. This group reported that despite the absence of breakfast in the overnight-fasted exercise,
166 energy intake during the test lunch was similar when exercise was performed in the fed-state.
167 Accordingly, energy intake and energy balance across the entire study period was significantly less
168 when exercise was performed in the overnight-fasted versus fed-state. Interestingly, the lower energy
169 balance with overnight-fasted exercise was attributable to reduced fat but not carbohydrate balance,
170 the importance of which are two-fold. Firstly, greater reductions in fat balance may be more likely to
171 induce favourable effects on body fat loss if sustained over time. Secondly, it is possible that the
172 maintenance of carbohydrate balance is more important and tightly regulated than fat balance possibly
173 due to finite carbohydrate storage capacity as has been previously suggested (28). In support of this
174 assertion, it has been reported that individuals who utilise more carbohydrate during exercise are more
175 likely to compensate for the energy expended during exercise with greater post-exercise energy intake
176 (29), and mice overexpressing hepatic *protein targeted to glycogen* (resulting in increased liver
177 glycogen concentrations under fasted and fed conditions), display reduced energy intake and
178 increased energy expenditure (30). As such, interventions that minimise carbohydrate oxidation
179 during exercise (such as overnight-fasted exercise) may serve to limit subsequent energy intake.

180

181 More recently, the effects of overnight-fasted versus fed-state exercise (i.e., breakfast) on energy
182 intake was examined over the course of an entire day, which may be more reflective of the potential
183 for long term impact on energy balance (31). The study by Bachman and colleagues reported that *ad*
184 *libitum* food (and energy) intake over a 24 h period was lower when exercise was performed prior to
185 breakfast consumption. Interestingly, reduced energy intake was not simply a function of breakfast
186 omission but food intake during meals and snacks consumed later in the day suggesting more
187 prolonged effects of overnight-fasted exercise on regulation of food intake. At this stage, the
188 involvement of metabolic (e.g., carbohydrate status) and/or modulation of appetite hormone
189 regulatory mechanisms in explaining this lower energy intake with overnight-fasted exercise has not
190 been resolved. The possibility of simply having less time in the day to consume food should also not
191 be excluded, and while speculative, if this is relevant then aspects of the purported benefits of time-
192 restricted feeding may be worthy for consideration (32). Importantly, the study by Backman and
193 colleagues did not quantify energy expenditure across the entire study period, thus the overall impact
194 of the interventions on energy balance was not reported. This may be particularly important, as in
195 conditions where free-living expenditure has been quantified, omission of breakfast *per se* (i.e.,
196 without exercise intervention) may transiently lower physical activity energy expenditure which
197 would impact on energy balance (33). These collective studies suggest that short-term studies that

198 encompass and allow for the behavioural responses to overnight-fasted versus fed-state exercise to
199 occur may be particularly useful for understanding the potential for long-term impacts upon
200 metabolism and health outcomes. However, the impact of altering carbohydrate oxidation on all
201 components of energy balance (including physical activity) in the post-exercise period currently
202 remains unknown, as do the mechanisms that link carbohydrate balance to any behavioural responses
203 in humans.

204

205 **Longer-term metabolic and health outcomes in response to overnight-fasted and fed-state** 206 **exercise**

207 It is clear from the previous sections that overnight-fasted versus fed-state exercise can modulate
208 metabolic and behavioural responses to a single bout of exercise. A relevant question is the extent to
209 which such short-term responses translate into long-term modifications in biomarkers or risk factors
210 for cardio-metabolic disease. If the feeding status around single exercise bouts is influential in
211 determining long-term adaptive responses to exercise, then it may in part explain why some
212 individuals do not always adapt to exercise training as would be predicted. The implication would be
213 that if all exercise training sessions within a training study were undertaken with standardisation of
214 pre-exercise nutrition, adaptive responses may be more consistent. However, to our knowledge there
215 are no studies investigating overnight-fasted versus fed state exercise training on the consistency or
216 variability of exercise adaptation. Indeed, with a few exceptions described below, the vast majority
217 of aerobic exercise training intervention studies focus on the exercise component rather consideration
218 of nutritional control or timing of food intake around exercise bouts.

219 The effects of overnight-fasted versus fed-state exercise on total body mass and indices of body
220 composition have been investigated in training studies conducted under differing states of energy
221 balance. Under iso-energetic and hypo-energetic conditions, when the state of energy balance is
222 matched between intervention groups, responses of total body mass, fat mass or fat-free mass did not
223 differ as a function of short-term (i.e., 4-6 weeks) overnight-fasted versus fed-state exercise training
224 (14, 34-36). While the effects on total body mass may be predictable, the lack of difference in body
225 fat reduction contrasts what could theoretically be expected based on previously observed increases
226 in daily fat oxidation and less positive (more negative) fat balance as a result of conducting overnight-
227 fasted exercise in acute studies. One of the aforementioned studies utilised a high-intensity interval
228 training program (34), which may not be favourable for increasing in fat oxidation during exercise.
229 As well, in all studies, the duration of training (i.e., 4-6 weeks) may have been insufficient to realise
230 the theoretical advantages of overnight-fasted exercise training on body fat mass. Previous studies of
231 exercise training *per se* would indicate that at least 12 weeks is necessary to induce measurable

232 reductions in body fat (37, 38). Thus, to date, experimental conditions may not have been optimised
233 to date to conclusively study if body composition can be improved with regular overnight-fasted
234 versus fed-state exercise training in iso- and hypo-energetic conditions. Indeed it could be that any
235 short-term changes in daily substrate oxidation and storage are balanced out over periods of days and
236 weeks such that body composition remains unaltered over the long-term unless there are clear
237 perturbations to long-term energy balance (39).

238 In contrast, a study conducted by Van Proeyen and colleagues indicated that effects of overnight-
239 fasted exercise training on body composition may be revealed during conditions of hyper-energetic
240 feeding (40). These researchers subjected three groups of lean, healthy men to 6 weeks of 30% excess
241 of habitual energy intake in the form a fat-rich (50% dietary energy) diet. Participants either
242 performed no exercise (Control, CON), overnight-fasted (FAST) or fed-state (FED) exercise four
243 times per week. In CON and FED body mass significantly increased as compared to pre-diet values
244 by ~3 and ~1.4 kg, respectively, while no significant changes were observed in FAST. While
245 interesting, it should be noted that despite apparent within-group differences in body mass gain no
246 significant between-group differences were observed between FED and FAST. Incidentally, body fat
247 assessed using skinfold thickness measurements increased in CON, but did not change significantly
248 in FED or FAST. Overall, there is a paucity of evidence to support a clear influence of overnight-
249 fasted versus fed-state exercise training on body weight and composition, at least when studied over
250 a short duration of training and in the state of energy balance is matched between intervention arms.
251 However, as we discuss later in the review, a more fruitful approach in the context of body weight
252 and composition may be to not clamp energy balance between interventions and allow natural
253 alterations in energy balance behaviours to occur outside of the specific controlled fasted or fed-
254 exercise prescription.

255 Exercising in the overnight-fasted versus fed-state has been linked to a number of responses that could
256 plausibly translate to long-term improvements in lipid and glucose metabolism. Adipose tissue plays
257 a critical role in the storage of ingested dietary fats with relevance for post-prandial lipemia and
258 minimising ectopic lipid storage. Indeed, high turnover of adipose tissue lipid stores has been
259 associated with improved metabolic health (41, 42) suggesting that frequent oxidation of adipose
260 tissue fatty acids increases the ability of adipose tissue to buffer lipid flux. Feeding status may
261 therefore alter adipose tissue physiology with resultant implications for health. Consistent with this
262 line of reasoning, a single bout of fed-state exercise blunts the effects typically seen with overnight-
263 fasted exercise on the expression of genes related to lipid metabolism, insulin sensitivity and glucose
264 uptake in adipose tissue (43). In a similar manner, fed-state exercise tends to blunt acute exercise-
265 related responses in skeletal muscle molecular pathways associated with the upregulation of

266 oxidative, lipid and carbohydrate metabolism (e.g., gene expression of FAT/CD36, CPT1, UCP3,
267 PDK4, GLUT4, AMPK α 2) (44, 45). As well, in young lean men overnight-fasted but not fed-state
268 exercise increased utilisation of IMTAG in Type 1 skeletal muscle fibres (14); high rates of IMTAG
269 turnover (i.e., storage and breakdown for NEFA oxidation) have been implicated in the maintenance
270 of muscle insulin sensitivity (46). Finally, while not unequivocal (35, 47), greater long-term changes
271 in markers of skeletal muscle training adaptation such as the protein contents of GLUT4, FAT/CD36
272 and FABP and the maximal activities of the mitochondrial enzymes citrate synthase and β -
273 hydroxyacyl coenzyme A dehydrogenase have been observed with overnight-fasted exercise training
274 (35, 40).

275 In general, the above evidence points to the potential for overnight-fasted exercise to promote greater
276 benefits to metabolic health outcomes than conducting regular exercise in the fed-state, although the
277 number of investigations in this area is remarkably limited. Summarising the evidence that is available
278 to date, Hansen and colleagues concluded that there does not appear to be clear impact of short-term
279 fed versus fasted-stated exercise training on overnight-fasted resting blood markers such as glucose,
280 insulin and NEFA; notably studies have generally been performed in young lean individuals (9). Only
281 the study by Van Proeyen and colleagues described previously, which adopted 6 weeks of hyper-
282 energetic fat rich feeding, has addressed the impact of overnight-fasted versus fed-state exercise
283 training on a dynamic measure of metabolic function (40). These authors found that the Matsuda
284 Insulin Sensitivity Index (calculated from an oral glucose tolerance test) was higher in the group that
285 performed overnight-fasted exercise training as compared to the no exercise control trial. No
286 significant differences were reported between fed-state exercise and no exercise control, with the
287 implication that fasted-state exercise improves glucose tolerance during a fat rich diet. The authors
288 rightly acknowledge that body mass gain in the control (and fed-exercise) trial but not the fasted-
289 exercise trial could contribute to the observed differential responses to insulin sensitivity.
290 Nonetheless, these data provide promising proof of concept for a role for overnight-fasted training in
291 enhancing benefits of exercise on glucose tolerance at least under conditions of excess energy intake,
292 which could have relevance within obesogenic environments.

293 As stated earlier, there is a clinical view that post-prandial exercise is preferable over fasted-state
294 exercise for the acute control of blood glucose, at least in patients living with type 2 diabetes (23).
295 However, if an individual performs fasted-state exercise it is not clear if the subsequent post-prandial
296 rises in blood glucose are pathological. As well, we also highlighted earlier that as compared to fasted-
297 state exercise, fed-state exercise can result in a worsening of subsequent post-prandial glucose control
298 (25). Again, the question arises as to whether this is potentially pathological or simply reflecting
299 short-term adaptive physiology. Our recent work examining post-prandial glucose fluxes after no

300 exercise, exercise performed in the overnight-fasted or fed state would suggest the latter (48).
301 Specifically, we observed in healthy young men that fed-state exercise increases glucose appearance
302 rates into the circulation during subsequent glucose ingestion, and this was explained by increases in
303 the appearance of the ingested glucose. However, this was met with increases in whole body glucose
304 disposal, such that the increased influx of glucose was appropriately cleared. Whether this applies in
305 other study populations remains to be determined, but it does lend support to the notion that the
306 responses of blood glucose to single bouts of exercise performed in the fed or fasted state are part of
307 normal physiology. What is perhaps more important is the adaptive stimulus provided by acute bouts
308 of exercise, for example in skeletal muscle, that when accrued over time results chronic changes in
309 the capacity to manage postprandial excursions in blood glucose (and lipids). In this respect, the work
310 from Van Proeyen and colleagues showing that aspects of glucose control may be preferentially
311 affected by consistent exercise training in the overnight-fasted versus fed-state (under conditions of
312 excess energy intake) is perhaps most revealing (40), although clearly there is a need to follow-up
313 this work in patients at risk of or living with disturbances in glucose control such as Type 2 diabetes.

314

315 **Conclusions and future research directions.**

316 There is little doubt that the investigation of how nutrient intake in an around exercise might modulate
317 the metabolic, molecular and adaptive responses to exercise training is of major current interest (e.g.,
318 (9, 10, 23, 49-51)). However, there is a need for further research in order to fully elucidate if
319 overnight-fasted exercise could be a means to optimise the health benefits of physical activity. For
320 example, the influence of a single bout of overnight-fasted versus fed-state exercise on aspects of
321 lipid metabolism and the molecular signals underpinning training adaptation should be studied further
322 in populations at-risk for cardio-metabolic disease. Characterising 24 h profiles of circulating
323 metabolite and hormones related to glucose and lipid metabolism in participant populations across
324 the health continuum would help to clarify their modulation overnight-fasted or fed-state exercise.
325 As well, there is a need to characterise the influence of overnight-fasted or fed-state exercise on short-
326 term energy balance behaviours in a range of study populations, as this could more adequately reflect
327 responses in 'real-world' settings. Generation of these data could provide clearer insights into which
328 populations and outcome measures may yield greater benefits from long-term exercise training in
329 overnight-fasted conditions.

330 There is also a need to extend exercise training studies performed in the overnight-fasted state versus
331 fed state for longer durations (i.e., ≥ 12 weeks) and into population groups with or at risk for cardio-
332 metabolic disease. In doing this, it would be important to integrate important clinical outcomes such

333 as body mass and composition, glucose tolerance, HBA1C and lipid profiles with measures of whole-
334 body and tissue specific metabolic function in order to gain further mechanistic insights (e.g., hepatic,
335 adipose and skeletal muscle adaptation). Given that daily variations in glycaemic and lipid profiles
336 could impact upon aspects of vascular function (e.g., endothelial function, microvascular perfusion),
337 this would also be an important area to explore. In conducting exercise training studies an important
338 consideration is whether or not to match the state of energy balance between intervention groups. As
339 there appears to be little compensation of energy intake to acute bouts of overnight-fasted exercise,
340 this approach appears most likely produce more consistent reductions in energy balance, which over
341 the long-term may provide complementary benefits to many outcome measures relevant to metabolic
342 health. Mechanistically, it is always appealing to tease out intervention effects independent from
343 changes in body mass (52). However, if additional health benefits are to be gained from overnight-
344 fasted versus fed-state exercise it is probably a moot point as to whether the effects arise through
345 direct or indirect mechanisms related to the intervention. Finally, while the focus of the present review
346 was on aerobic exercise, future work investigating the health impact of performing others forms of
347 exercise such as resistance training (53) or combined resistance and aerobic training (concurrent
348 exercise) in the overnight-fasted versus fed-state would be worthwhile.

349 In conclusion, conducting aerobic exercise in the overnight-fasted versus fed-sate can differentially
350 modulate aspects of metabolism (**Figure 1**) and it is possible that this could influence the overall
351 adaptive response to exercise training for health benefits. If this is the case, advice on when to exercise
352 with respect to food intake could be considered for incorporation into physical activity guidelines in
353 general or for specific sub-populations seeking to optimise the health or therapeutic benefits of
354 exercise. However, further research, some of which is highlighted in this review, is needed before we
355 can answer the question as to whether exercise is best served on an empty stomach.

356

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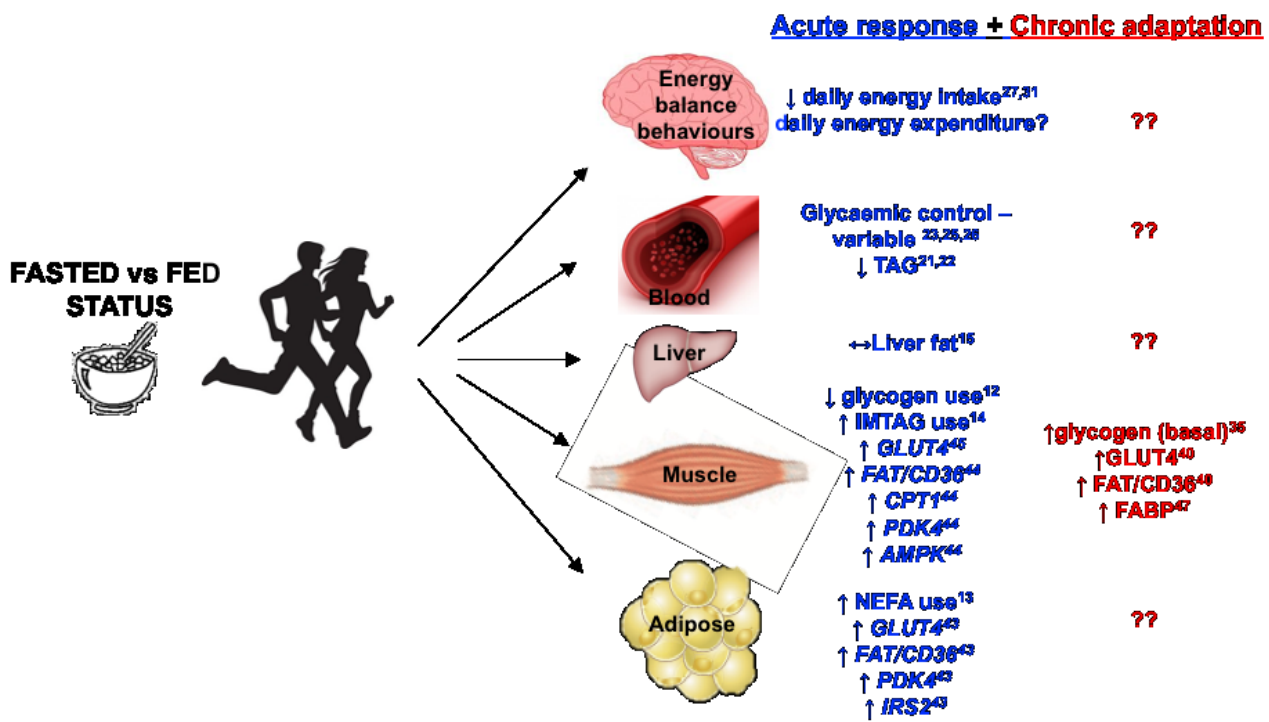
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371 **Conflict of Interest**

372 None.

373



374

375 **Figure 1.** Major metabolic and behavioural factors influenced by aerobic exercise performed in the
 376 overnight-fasted versus fed state. Acute response refers to a single bout of exercise. Chronic
 377 adaptation refers to the culmination of single bouts of exercise over a period of weeks to months as a
 378 result of undertaking an exercise training program. The figure includes results from studies that used
 379 a range of study populations and different experimental designs and as such should be regarded as
 380 conceptual rather than definitive. Superscript refers to the appropriate supporting reference.

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