

No acute effect of reduced-exertion high intensity interval training (REHIT) on insulin sensitivity

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1 **ABSTRACT**

2

3 We have previously demonstrated that reduced-exertion high-intensity interval training
4 (REHIT), requiring a maximum of two 20-s all out cycling sprints in a 10-min exercise session,
5 improves insulin sensitivity in sedentary men over a 6-week training intervention. However,
6 the acute effects of REHIT on insulin sensitivity have not previously been described. In this
7 study fourteen men and women (mean±SD age: 23±5 y; BMI 22.7±4.7 kg·m⁻²; $\dot{V}O_2$ max:
8 37.4±8.6 mL·kg⁻¹·min⁻¹) underwent oral glucose tolerance testing 14-16 hours after an acute
9 bout of reduced-exertion high-intensity interval training (2 x 20-s all-out sprints; REHIT),
10 moderate-vigorous aerobic exercise (45 minutes at ~75% $\dot{V}O_2$ max; AER), and a resting
11 control condition (REST). Neither REHIT nor AER were associated with significant changes
12 in glucose AUC (REHIT 609±98 vs. AER 651±85 vs. REST 641±126 mmol·l⁻¹·120 min), insulin
13 AUC (REHIT 30.9±15.4 vs. AER 31.4±13.0 vs. REST 35.0±18.5 nmol·l⁻¹·120 min) or insulin
14 sensitivity estimated by the Cederholm index (REHIT 86±20 vs. AER 79±13 vs. REST 82±24
15 mg·l⁻²·mmol⁻¹·mU⁻¹·min⁻¹). These data suggest that improvements in insulin sensitivity
16 following a chronic REHIT intervention are the result of training adaptations rather than acute
17 effects of the last exercise session.

18 INTRODUCTION

19

20 The finding that lack of time is a major barrier to performing regular exercise has led to a rise
21 in studies investigating high-intensity interval training (HIT) as a time-efficient method for
22 improving aerobic fitness and metabolic health [16]. However, it is noteworthy that due to the
23 required recovery intervals the time-commitment of most HIT protocols is generally similar to
24 current guidelines for aerobic exercise. We [26] and others [18] have recently demonstrated
25 that a modified HIT protocol requiring two or three 20-s Wingate sprints in a 10-min cycling
26 session (reduced-exertion HIT; REHIT) can improve aerobic capacity in sedentary men and
27 women, and insulin sensitivity in men. These benefits were observed despite the low total
28 time-commitment (30 min per week) and manageable ratings of perceived exertion,
29 suggesting that REHIT may be a suitable alternative or adjunct to current exercise
30 recommendations [26]. However, more studies are required to further characterise the acute
31 and chronic effects of REHIT on human health and metabolism, both in isolation and in
32 combination with more traditional exercise modes.

33

34 Insulin sensitivity is an important biomarker in the development of type 2 diabetes and
35 metabolic syndrome and is a primary target for preventative intervention [8,33]. The effects of
36 exercise on insulin sensitivity are thought to be largely explained by improved glucose uptake
37 in skeletal muscles [9,10]. From this perspective, exercise has been shown to exert three
38 distinct regulatory roles on skeletal muscle glucose uptake. Firstly, skeletal muscle
39 contractions themselves recruit glucose transporter 4 (GLUT4) molecules to the cell
40 membrane and increase glucose uptake in an intensity dependent manner, through signalling
41 pathways that are independent of and additive to insulin [14,29,34,38,41]. This effect is
42 transient, subsiding completely ~2-3 hours after the cessation of the muscle contractions [24].
43 However, it appears to be replaced by an acute enhancement of insulin-stimulated recruitment
44 of GLUT4 and hence postprandial glucose disposal in the exercised muscle, which can be
45 detected for 24-48 hours post-exercise, and which appears to track with the replenishment of

46 skeletal muscle glycogen stores [2,5,19]. Lastly, the cumulative effect of many repeated bouts
47 of acute exercise (i.e., exercise training) can bring about a favourable change in skeletal
48 muscle phenotype and body composition which correlates with a more prolonged increase in
49 insulin sensitivity that can be detected for several days after the final training bout [9].

50

51 The improvements in insulin sensitivity in men following REHIT have been noted at 3 days
52 following the final exercise session and were ascribed to chronic training adaptations [18,26].
53 However, this contention remains unsubstantiated since no study has examined the effects of
54 a single bout of REHIT on insulin sensitivity. Understanding the role of both single and
55 accumulated bouts of exercise on parameters of metabolic health is important from the
56 perspective of exercise prescription. Therefore, the aim of this study was to determine the
57 impact of a single bout of REHIT on insulin sensitivity measured the following day in
58 comparison to a bout of moderate-vigorous aerobic exercise and a no-exercise control
59 condition. Based on the findings of Brestoff et al [3], our primary hypothesis was that there
60 would be no acute effect of REHIT on insulin sensitivity, whilst our secondary hypothesis
61 speculated there would be an increase in insulin sensitivity following an acute bout of
62 moderate-vigorous intensity aerobic exercise.

63 MATERIALS AND METHODS

64

65 **Participants**

66 Fourteen healthy young men (n=8) and women (n=6) gave their written informed consent to
67 take part in this study (mean±SD age: 23±5 y; BMI 22.7±4.7 kg·m⁻²; $\dot{V}O_2$ max: 37.4±8.6 mL·kg⁻¹·min⁻¹). All participants were sedentary or recreationally active according to the International
68 Physical Activity Questionnaire. The study was approved by the Heriot-Watt University School
69 of Life Sciences Ethics Committee and conducted in accordance with the *Declaration of*
70 *Helsinki* and ethical standards for sport and exercise science research [20].
71

72

73 **Baseline Testing and Familiarisation**

74 Prior to the main trials participants visited the laboratory on four occasions. During the initial
75 visit maximal oxygen uptake capacity ($\dot{V}O_2$ max) was determined during an incremental cycling
76 test to volitional exhaustion on an electrically-braked cycle ergometer (25 W·min⁻¹ ramp; Lode
77 Excalibur Sport, the Netherlands) with analysis of $\dot{V}O_2$ using an online metabolic cart
78 (SensorMedics, Bilthoven, the Netherlands). $\dot{V}O_2$ max was taken as the highest value of a 15-
79 breath rolling average. Participants performed two familiarisation sessions for the REHIT trial
80 and one for the aerobic exercise trial (AER). The REHIT familiarisation sessions were used to
81 familiarise participants with the procedures and the effort required during Wingate-type sprints.
82 The AER session was used to check the intensity predicted to elicit 75% $\dot{V}O_2$ max. Participants
83 cycled for 15-min at the prescribed intensity and $\dot{V}O_2$ was measured continuously throughout
84 (SensorMedics, Bilthoven, the Netherlands). If necessary, adjustments were made to the
85 intensity used during the main trials.

86

87 **Experimental Procedures**

88 Participants completed three main experimental trials (REHIT, AER and REST) in a
89 randomised cross-over design, with each trial taking place over a 2-day period. During each

90 trial participants underwent an oral glucose tolerance test (OGTT) on the morning after
91 performing either: 1) a single bout of REHIT, 2) a single bout of moderate-vigorous intensity
92 aerobic exercise (AER), or 3) a no-exercise control condition (REST). Each trial was separated
93 by at least 1 week and prior to each trial participants were asked to refrain from performing
94 strenuous/prolonged physical activities and consuming alcohol/caffeine for 2 days and 1 day
95 respectively.

96

97 On the evening prior to each OGTT, participants attended the laboratory between 4:30 pm
98 and 7:00 pm to perform the exercise session. Participants were given a standardised evening
99 meal (energy: 3234 ± 494 kJ; carbohydrate: 107 ± 17 g; fat: 21 ± 7 g; protein: 35 ± 10 g) 30 min
100 after completion of the exercise bout. For each participant the time of attendance was
101 consistent between conditions. Participants fasted overnight and returned to the laboratory
102 the following morning between 7:00 am and 9:30 am. An OGTT was performed after 15 min
103 of seated rest.

104

105 ***Exercise Protocols***

106 All exercise protocols were performed on an electrically-braked cycle ergometer (Lode
107 Excalibur Sport, the Netherlands). The aerobic exercise protocol involved 45 min of cycling at
108 an intensity predicted to elicit $\sim 75\%$ of $\dot{V}O_2$ max as previously used by Brestoff et al. [3].
109 Cadence was self-selected and the exercise was completed in three intervals of 15 min with
110 2 min of resting recovery in between. $\dot{V}O_2$ was determined during the final 5 min of the first
111 bout (SensorMedics, Bilthoven, the Netherlands) and heart rate was measured throughout
112 (Polar Electro, Vansbro, Sweden). The REHIT condition involved 10 min of unloaded pedalling
113 and two 20-s Wingate sprints at 3:00 min and 6:40 min as previously described [26]. Just
114 before each sprint, participants increased their pedal cadence to their maximal speed, a
115 braking torque was applied to the ergometer (0.70 and 0.60 $\text{Nm}\cdot\text{kg}^{-1}$ for men and women,
116 respectively), and participants sprinted maximally against the braking torque for 20 s.

117 **Oral Glucose Tolerance Test**

118 A fasting blood sample was obtained from a forearm vein by venepuncture using the
119 vacutainer system, after which 75 g of anhydrous glucose (Fisher Scientific, Loughborough,
120 UK) in 100 mL of water was orally ingested and further blood samples collected at 60 and 120
121 min after glucose ingestion. Blood samples were collected into cooled plastic tubes containing
122 EDTA and stored on ice during the OGTT. Samples were centrifuged for 10 min at 2000 g and
123 4°C to separate the plasma, which was stored at -20°C until analysis. Plasma glucose
124 concentration was determined in duplicate with a CV of <1% (YSI Stat 2300, Yellow Spring
125 Instruments, Yellow Spring, OH). Plasma insulin concentrations were measured in duplicate
126 using a commercially available ELISA with a CV of 4% (Invitrogen, UK). Area under the curve
127 (AUC) for plasma glucose and insulin responses was calculated using the trapezoid rule,
128 whilst insulin sensitivity was determined using the Cederholm Index [6].

129

130 **Statistics**

131 . Statistical analysis was performed using SPSS statistical software. To simplify analysis and
132 interpretation of an otherwise complex data set, the OGTT responses for each condition were
133 converted into simple summary statistics (i.e., within subject fasting, total AUC and insulin
134 sensitivity scores). As two-way repeated measures ANOVAs revealed no gender × group
135 interactions for any OGTT-derived variables, all data was pooled and comparisons were made
136 using 1-factor repeated measures ANOVA with *post hoc* Ryan Holm Bonferroni corrected t-
137 tests if appropriate. Significance was accepted at $P < 0.05$. Exercise characterisation data are
138 presented as mean \pm SD, whilst the effects of the exercise bouts on OGTT-derived variables
139 is presented in text as the mean change from the REST condition with 95% confidence
140 intervals. Data in figures are presented as mean \pm SD unless otherwise stated.

141 **RESULTS**

142

143 ***Exercise Characteristics***

144 During the AER exercise session participants cycled at $76\pm 4\%$ of $\dot{V}O_2\text{max}$ and this elicited
145 $86\pm 7\%$, $90\pm 6\%$ and $91\pm 6\%$ of maximal heart rate (HRmax) during bouts 1, 2 and 3
146 respectively. Peak, mean and minimum power output for REHIT were 12.2 ± 2.1 , 6.6 ± 1.5 and
147 $4.4\pm 1.4 \text{ W}\cdot\text{kg}^{-1}$ for the first sprint, and 11.9 ± 2.0 , 5.9 ± 1.5 and $3.9\pm 1.3 \text{ W}\cdot\text{kg}^{-1}$ for the second
148 sprint. Heart rate peaked at $93\pm 4\%$ and $94\pm 3\%$ of HRmax for the first and second sprints
149 respectively. The total amount of work performed in the AER and REHIT bouts was
150 312.8 ± 118.3 and $16.7\pm 5.4 \text{ kJ}$, respectively.

151

152 ***Glucose and Insulin Responses to the OGTTs***

153 The insulin and glucose responses to the OGTTs are presented in Figure 1. There was no
154 effect of either exercise condition on fasting glucose concentration (mean change [95% CI's]:
155 REHIT: $-0.066 [-0.192, 0.059] \text{ mmol}\cdot\text{l}^{-1}$; AER: $-0.090 [-0.273, 0.093] \text{ mmol}\cdot\text{l}^{-1}$) or fasting insulin
156 concentrations (REHIT: $-0.006 [-0.021, 0.008] \text{ nmol}\cdot\text{l}^{-1}$; AER: $-0.017 [-0.038, 0.005] \text{ nmol}\cdot\text{l}^{-1}$) when
157 compared with REST. Similarly, neither REHIT or AER were associated with any changes in
158 glucose AUC (REHIT: $-32.3 [-77.8, 13.1] \text{ mmol}\cdot\text{l}^{-1}\cdot 120\text{min}$; AER: $+9.38 [-45.9, 64.7] \text{ mmol}\cdot\text{l}^{-1}\cdot 120\text{min}$),
159 insulin AUC (REHIT: $-4.19 [-10.7, 2.28] \text{ nmol}\cdot\text{l}^{-1}\cdot 120\text{min}$; AER: $-3.73 [-8.97, 1.52] \text{ nmol}\cdot\text{l}^{-1}\cdot 120\text{min}$)
160 or insulin sensitivity (REHIT: $+4.91 [-0.941, 10.8] \text{ mg}\cdot\text{l}^2\cdot\text{mmol}^{-1}\cdot\text{mU}^{-1}\cdot\text{min}^{-1}$;
161 AER: $-2.64 [-12.1, 6.86] \text{ mg}\cdot\text{l}^2\cdot\text{mmol}^{-1}\cdot\text{mU}^{-1}\cdot\text{min}^{-1}$) when compared with REST.

162 **DISCUSSION**

163

164 The aim of this study was to examine the effect of a single bout of REHIT on insulin sensitivity
165 measured the following day in comparison to a single bout of moderate-vigorous aerobic
166 exercise and a no-exercise control condition. In agreement with our primary hypothesis, these
167 data demonstrate that a single bout of REHIT does not improve insulin sensitivity, and this
168 strengthens our previous contention that the increase in insulin sensitivity detected 3 days
169 following a 6-week REHIT intervention in sedentary men can be ascribed to chronic training
170 adaptations [18,26]. In contrast, our secondary hypothesis was not supported, with no
171 increase in insulin sensitivity observed following a single bout of moderate-vigorous intensity
172 aerobic exercise.

173

174 Our finding that there was no acute impact of REHIT on insulin sensitivity is in line with recent
175 acute studies demonstrating no change in OGTT-derived insulin sensitivity 14-16 hours
176 following single bouts of HIT consisting of five sprints at $\sim 125\%$ $\dot{V}O_2\text{max}$ [3] or four 30-s
177 Wingate sprints [39]. Similarly, HIT did not appear to attenuate the systemic glucose or insulin
178 response to a high-fat mixed meal challenge administered 14 hours post-exercise, although
179 the overall lipemic response was reduced [12,13]. Conversely, Ortega et al. [31] reported a
180 significant increase in insulin sensitivity measured using intravenous glucose tolerance testing
181 (IVGTT) which lasted for at least 48 hours after four 30-s Wingate sprints, whilst Little et al.
182 [25] reported a reduction in mean 24-h glucose concentrations and 24-h postprandial glucose
183 AUC following ten 1-min sprints at $>90\%$ HR_{max} in a small cohort of overweight men. The
184 reason for these discrepancies is unclear but may be related to the different methods of
185 assessing insulin sensitivity and glycaemic control (IVGTT and continuous glucose monitoring
186 vs. OGTT or oral mixed meals). Further studies are warranted examining the acute effects of
187 HIT/REHIT, both in isolation and in combination with more traditional exercise modes, on
188 insulin sensitivity using the gold standard hyperinsulinemic clamp in a range of populations.
189 Nevertheless, the current data have important implications for the prescription of REHIT (in

190 isolation) as a preventative intervention in the general population. If reductions in postprandial
191 systemic insulin and glucose concentrations are the primary targeted endpoint then single
192 bouts will not be effective; rather REHIT needs to be repeated regularly over several weeks in
193 order for adaptations to be accrued.

194

195 We could detect no increase in insulin sensitivity measured 14-16 hours following an acute
196 bout of vigorous intensity aerobic exercise. This is in contrast to recent data from Brestoff et
197 al. [3] who demonstrated a 25% reduction in insulin AUC during an OGTT using a comparable
198 cohort of participants, exercise bout and post-exercise time point. However, the literature as
199 a whole is somewhat inconsistent, with many studies in healthy lean individuals reporting no
200 measurable changes at similar time-points following acute aerobic exercise of varying
201 intensities and durations [1,2,11,21,35,37], whilst others show improvements for as long as
202 48 hours post-exercise exercise [27,32,36,40]. The lack of change in our study may be
203 explained by a combination of two factors. Firstly, the timing and composition of post-exercise
204 feeding appears to have a strong influence on the response. Several studies show that
205 restriction of carbohydrate intake appears to prolong any increase in insulin sensitivity post-
206 exercise both in rodents [5,19,23] and in humans [2,22,30]. This makes sense from an
207 evolutionary perspective, as any metabolic acceleration following exercise is presumably an
208 attempt to restore intramuscular substrate stores as quickly as possible so that further exercise
209 may be performed [7]. Secondly, there is evidence that individuals with lower baseline levels
210 of insulin sensitivity tend to exhibit a more prolonged increase in post-exercise insulin
211 sensitivity which can be detected even after several meals have been consumed [4,11,15,28].
212 This is perhaps reflective of the decrement in insulin action resulting in delayed restoration of
213 intramuscular substrate stores after exercise, thereby necessitating a more prolonged
214 increase in insulin sensitivity. In any case, given that our cohort of participants already had a
215 healthy level of insulin sensitivity, and we fed them a meal containing ~100 g of carbohydrate

216 30 min post-exercise, it is perhaps not all that surprising that we observed no change in insulin
217 sensitivity following the aerobic exercise bout in the current study.

218

219 There are several limitations to the current analysis which provide opportunity for further study.
220 Firstly, we could only include three time-points during the OGTT for our calculation of insulin
221 sensitivity. Whilst this protocol was sensitive enough to detect the relatively large changes in
222 insulin sensitivity observed following the REHIT training intervention [26], it must be
223 acknowledged that we may have missed more subtle changes in the current analysis. It would
224 therefore be useful to repeat the current study using the more sensitive gold standard
225 euglycemic clamp methodology. Secondly, we only included a 14-16 hour post-exercise time
226 point in this study and cannot therefore rule out that REHIT impacts on insulin sensitivity in
227 the more immediate post-exercise period (i.e., in response to the first feeding). Lastly, in order
228 to be able to make firm comparisons between the current acute study and the previous training
229 intervention [26] we recruited a similar cohort of participants who, although sedentary, were
230 young, lean and with a healthy level of insulin sensitivity. It is therefore necessary to
231 investigate the acute impact of REHIT in populations with insulin resistance, particularly in
232 light of the recent finding that other models of HIT substantially improve glycaemic control in
233 middle aged men presenting with T2D [17].

234

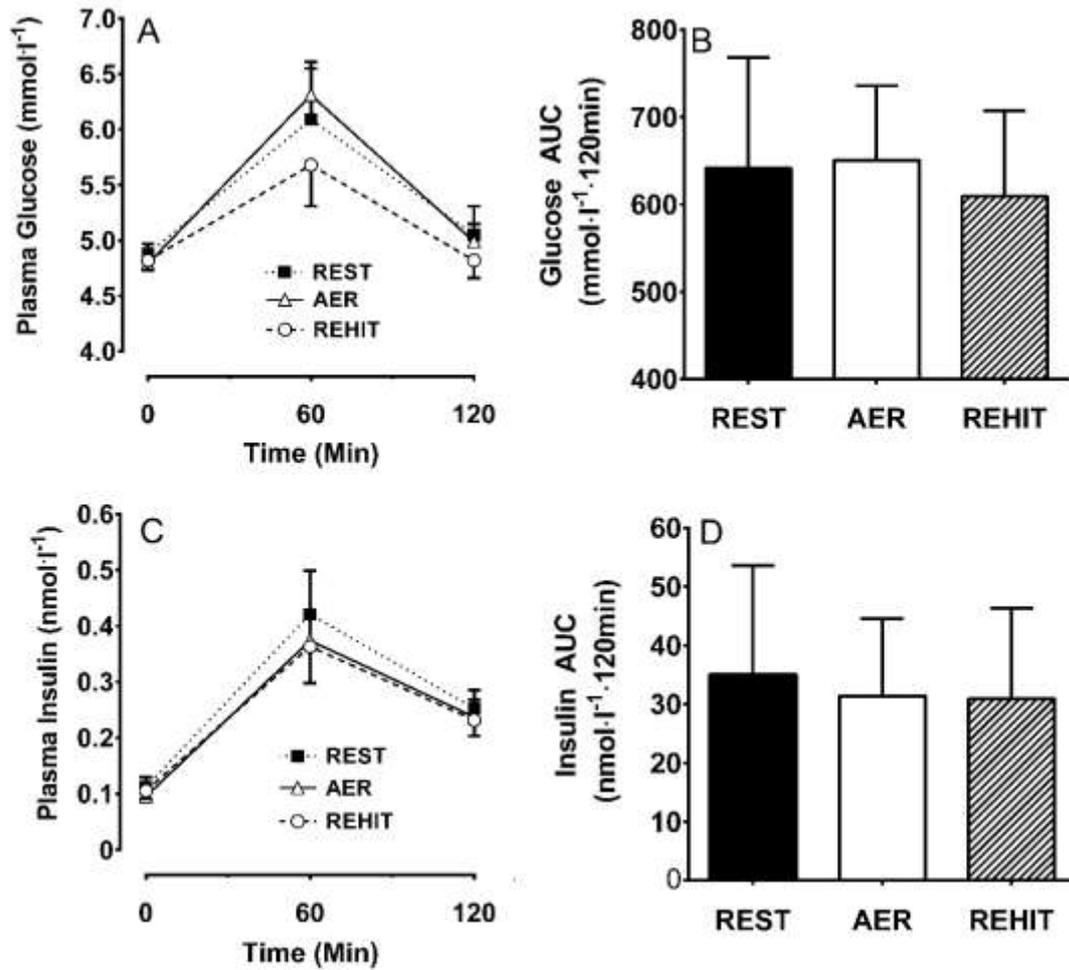
235 To summarise, the data of the present study demonstrate no effect of an acute bout of REHIT
236 on insulin sensitivity. This suggests that the potential utility of REHIT for improving insulin
237 sensitivity may be limited to a chronic training response.

238 REFERENCES

- 239 1. Baynard T, Franklin RM, Goulopoulou S, Carhart R, Jr., Kanaley JA. Effect of single
240 vs multiple bouts of exercise on glucose control in women with type 2 diabetes.
241 *Metabolism* 2005; 54: 989-994
- 242 2. Bogardus C, Thuillez P, Ravussin E, Vasquez B, Narimiga M, Azhar S. Effect of muscle
243 glycogen depletion on in vivo insulin action in man. *J Clin Invest* 1983; 72: 1605-1610
- 244 3. Brestoff JR, Clippinger B, Spinella T, von Duvillard SP, Nindl BC, Arciero PJ. An acute
245 bout of endurance exercise but not sprint interval exercise enhances insulin sensitivity.
246 *Appl Physiol Nutr Metab* 2009; 34: 25-32
- 247 4. Burstein R, Polychronakos C, Toews CJ, MacDougall JD, Guyda HJ, Posner BI. Acute
248 reversal of the enhanced insulin action in trained athletes: association with insulin
249 receptor changes. *Diabetes* 1985; 34: 756-760
- 250 5. Cartee GD, Young DA, Sleeper MD, Zierath J, Wallberg-Henriksson H, Holloszy JO.
251 Prolonged increase in insulin-stimulated glucose transport in muscle after exercise.
252 *Am J Physiol* 1989; 256: E494-499
- 253 6. Cederholm J, Wibell L. Insulin release and peripheral sensitivity at the oral glucose
254 tolerance test. *Diabetes Res Clin Pract* 1990; 10: 167-175
- 255 7. Chakravarthy MV, Booth FW. Eating, exercise, and "thrifty" genotypes: connecting the
256 dots toward an evolutionary understanding of modern chronic diseases. *J Appl Physiol*
257 2004; 96: 3-10
- 258 8. DeFronzo RA, Tripathy D. Skeletal muscle insulin resistance is the primary defect in
259 type 2 diabetes. *Diabetes Care* 2009; 32 Suppl 2: S157-163
- 260 9. Dela F, Larsen JJ, Mikines KJ, Ploug T, Petersen LN, Galbo H. Insulin-stimulated
261 muscle glucose clearance in patients with NIDDM. Effects of one-legged physical
262 training. *Diabetes* 1995; 44: 1010-1020
- 263 10. Dela F, Mikines KJ, von Linstow M, Secher NH, Galbo H. Effect of training on insulin-
264 mediated glucose uptake in human muscle. *Am J Physiol* 1992; 263: E1134-1143
- 265 11. Devlin JT, Horton ES. Effects of prior high-intensity exercise on glucose metabolism in
266 normal and insulin-resistant men. *Diabetes* 1985; 34: 973-979
- 267 12. Freese EC, Levine AS, Chapman DP, Hausman DB, Cureton KJ. Effects of acute
268 sprint interval cycling and energy replacement on postprandial lipemia. *J Appl Physiol*
269 2011; 111: 1584-1589
- 270 13. Gabriel B, Ratkevicius A, Gray P, Frenneaux MP, Gray SR. High-intensity exercise
271 attenuates postprandial lipaemia and markers of oxidative stress. *Clin Sci (Lond)* 2012;
272 123: 313-321
- 273 14. Gao J, Ren J, Gulve EA, Holloszy JO. Additive effect of contractions and insulin on
274 GLUT-4 translocation into the sarcolemma. *J Appl Physiol* 1994; 77: 1597-1601

- 275 15. Gill JM, Al-Mamari A, Ferrell WR, Cleland SJ, Packard CJ, Sattar N, Petrie JR, Caslake
276 MJ. Effects of prior moderate exercise on postprandial metabolism and vascular
277 function in lean and centrally obese men. *J Am Coll Cardiol* 2004; 44: 2375-2382
- 278 16. Gillen JB, Gibala MJ. Is high-intensity interval training a time-efficient exercise strategy
279 to improve health and fitness? *Appl Physiol Nutr Metab* 2014; 39: 409-412
- 280 17. Gillen JB, Little JP, Punthakee Z, Tarnopolsky MA, Riddell MC, Gibala MJ. Acute high-
281 intensity interval exercise reduces the postprandial glucose response and prevalence
282 of hyperglycaemia in patients with type 2 diabetes. *Diabetes Obes Metab* 2012; 14:
283 575-577
- 284 18. Gillen JB, Percival ME, Skelly LE, Martin BJ, Tan RB, Tarnopolsky MA, Gibala MJ.
285 Three minutes of all-out intermittent exercise per week increases skeletal muscle
286 oxidative capacity and improves cardiometabolic health. *PLoS One* 2014; 9: e111489
- 287 19. Gulve EA, Cartee GD, Zierath JR, Corpus VM, Holloszy JO. Reversal of enhanced
288 muscle glucose transport after exercise: roles of insulin and glucose. *Am J Physiol*
289 1990; 259: E685-691
- 290 20. Harriss DJ, Atkinson G. Ethical standards in sport and exercise science research: 2014
291 update. *Int J Sports Med* 2013; 34: 1025-1028
- 292 21. Hasson RE, Granados K, Chipkin S, Freedson PS, Braun B. Effects of a single
293 exercise bout on insulin sensitivity in black and white individuals. *J Clin Endocrinol*
294 *Metab* 2010; 95: E219-223
- 295 22. Holtz KA, Stephens BR, Sharoff CG, Chipkin SR, Braun B. The effect of carbohydrate
296 availability following exercise on whole-body insulin action. *Appl Physiol Nutr Metab*
297 2008; 33: 946-956
- 298 23. Kawanaka K, Nolte LA, Han DH, Hansen PA, Holloszy JO. Mechanisms underlying
299 impaired GLUT-4 translocation in glycogen-supercompensated muscles of exercised
300 rats. *Am J Physiol* 2000; 279: E1311-1318
- 301 24. Lauritzen HP, Galbo H, Toyoda T, Goodyear LJ. Kinetics of contraction-induced
302 GLUT4 translocation in skeletal muscle fibers from living mice. *Diabetes* 2010; 59:
303 2134-2144
- 304 25. Little JP, Jung ME, Wright AE, Wright W, Manders RJ. Effects of high-intensity interval
305 exercise versus continuous moderate-intensity exercise on postprandial glycemic
306 control assessed by continuous glucose monitoring in obese adults. *Appl Physiol Nutr*
307 *Metab* 2014; 39: 835-841
- 308 26. Metcalfe RS, Babraj JA, Fawcner SG, Vollaard NB. Towards the minimal amount of
309 exercise for improving metabolic health: beneficial effects of reduced-exertion high-
310 intensity interval training. *Eur J Appl Physiol* 2012; 112: 2767-2775
- 311 27. Mikines KJ, Sonne B, Farrell PA, Tronier B, Galbo H. Effect of physical exercise on
312 sensitivity and responsiveness to insulin in humans. *Am J Physiol* 1988; 254: E248-
313 259

- 314 28. Nelson RK, Horowitz JF. Acute exercise ameliorates differences in insulin resistance
315 between physically active and sedentary overweight adults. *Appl Physiol Nutr Metab*
316 2014; 39: 811-818
- 317 29. Neshar R, Karl IE, Kipnis DM. Dissociation of effects of insulin and contraction on
318 glucose transport in rat epitrochlearis muscle. *Am J Physiol* 1985; 249: C226-232
- 319 30. Newsom SA, Schenk S, Thomas KM, Harber MP, Knuth ND, Goldenberg N, Horowitz
320 JF. Energy deficit after exercise augments lipid mobilization but does not contribute to
321 the exercise-induced increase in insulin sensitivity. *J Appl Physiol* 2010; 108: 554-560
- 322 31. Ortega JF, Fernández-Elías VE, Hamouti N, García-Pallarés J, Mora-Rodriguez R.
323 Higher insulin-sensitizing response after sprint interval compared to continuous
324 exercise. *Int J Sports Med* 2015; 36: 209-214
- 325 32. Perseghin G, Price TB, Petersen KF, Roden M, Cline GW, Gerow K, Rothman DL,
326 Shulman GI. Increased glucose transport-phosphorylation and muscle glycogen
327 synthesis after exercise training in insulin-resistant subjects. *N Engl J Med* 1996; 335:
328 1357-1362
- 329 33. Petersen KF, Dufour S, Savage DB, Bilz S, Solomon G, Yonemitsu S, Cline GW,
330 Befroy D, Zeman L, Kahn BB, Papademetris X, Rothman DL, Shulman GI. The role
331 of skeletal muscle insulin resistance in the pathogenesis of the metabolic syndrome.
332 *Proc Natl Acad Sci USA* 2007; 104: 12587-12594
- 333 34. Ploug T, Galbo H, Richter EA. Increased muscle glucose uptake during contractions:
334 no need for insulin. *Am J Physiol* 1984; 247: E726-731
- 335 35. Short KR, Pratt LV, Teague AM. The acute and residual effect of a single exercise
336 session on meal glucose tolerance in sedentary young adults. *J Nutr Metab* 2012;
337 2012: 278678
- 338 36. Short KR, Pratt LV, Teague AM, Man CD, Cobelli C. Postprandial improvement in
339 insulin sensitivity after a single exercise session in adolescents with low aerobic fitness
340 and physical activity. *Pediatr Diabetes* 2013; 14: 129-137
- 341 37. Venables MC, Shaw CS, Jeukendrup AE, Wagenmakers AJ. Effect of acute exercise
342 on glucose tolerance following post-exercise feeding. *Eur J Appl Physiol* 2007; 100:
343 711-717
- 344 38. Wallberg-Henriksson H, Constable SH, Young DA, Holloszy JO. Glucose transport into
345 rat skeletal muscle: interaction between exercise and insulin. *J Appl Physiol* 1988; 65:
346 909-913
- 347 39. Whyte LJ, Ferguson C, Wilson J, Scott RA, Gill JM. Effects of single bout of very high-
348 intensity exercise on metabolic health biomarkers in overweight/obese sedentary men.
349 *Metabolism* 2013; 62: 212-219
- 350 40. Young JC, Enslin J, Kuca B. Exercise intensity and glucose tolerance in trained and
351 nontrained subjects. *J Appl Physiol* 1989; 67: 39-43
- 352 41. Zorzano A, Balon TW, Goodman MN, Ruderman NB. Additive effects of prior exercise
353 and insulin on glucose and AIB uptake by rat muscle. *Am J Physiol* 1986; 251: E21-26
354



355

356 **Figure 1** Plasma glucose (A+B) and insulin (C+D) responses to acute exercise. For clarity,
 357 the responses over time to the OGTT are presented as mean±SEM, whilst the AUC data is
 358 presented as mean±SD. REHIT: reduced-exertion HIT, AER: aerobic exercise, REST: no
 359 exercise control.