
This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

The efficacy of downhill running as a method to enhance running economy in trained distance runners

PLEASE CITE THE PUBLISHED VERSION

<https://doi.org/10.1080/17461391.2018.1449892>

PUBLISHER

© European College of Sport Science. Published by Taylor and Francis

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This is an Accepted Manuscript of an article published by Taylor & Francis in European Journal of Sport Science on 21 March 2018, available online: <http://www.tandfonline.com/10.1080/17461391.2018.1449892>.

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Shaw, Andrew J., Stephen A. Ingham, and Jonathan Folland. 2019. "The Efficacy of Downhill Running as a Method to Enhance Running Economy in Trained Distance Runners". figshare.
<https://hdl.handle.net/2134/32841>.

1 **The efficacy of downhill running as a method to enhance running economy**
2 **in trained distance runners**

3 Original investigation

4 Andrew J. Shaw^{1,2}, Stephen A. Ingham^{1,3}, Jonathan P. Folland²

5 ¹ English Institute of Sport, Loughborough University, Loughborough, UK; ² School of
6 Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK;

7 ³Supporting Champions, Loughborough, UK

8 Corresponding author:

9 Andrew Shaw, English Institute of Sport, Loughborough University, Ashby Road,
10 Loughborough, Leicestershire, LE11 3TU, United Kingdom

11 Tel: +44 (0)7846187628

12 Fax: +44 (0)1509 226301

13 Email: andrew.shaw@eis2win.co.uk

14 Running heading: Effect of downhill running on running economy

15 Abstract word count:249

16 Article word count:3438

17

18

19

20

21

22

23

24 **Abstract**

25 Running downhill, in comparison to running on the flat, appears to involve an exaggerated
26 stretch shortening cycle (SSC) due to greater impact loads and higher vertical velocity on
27 landing, whilst also incurring a lower metabolic cost. Therefore, downhill running could
28 facilitate higher volumes of training at higher speeds whilst performing an exaggerated SSC,
29 potentially inducing favourable adaptations in running mechanics and running economy. This
30 investigation assessed the efficacy of a supplementary 8 week programme of downhill running
31 as a means of enhancing running economy in well trained distance runners. Nineteen athletes
32 completed supplementary downhill (-5% gradient; $n=10$) or flat ($n=9$) run training twice a week
33 for 8 weeks within their habitual training. Participants trained at a standardised intensity based
34 on the velocity of lactate turnpoint (vLTP), with training volume increased incrementally
35 between weeks. Changes in energy cost of running (E_C) and vLTP were assessed on both flat
36 and downhill gradients, in addition to maximal oxygen uptake ($\dot{V}O_{2max}$). No changes in E_C were
37 observed during flat running following downhill (1.22 ± 0.09 vs 1.20 ± 0.07 Kcal \cdot kg $^{-1}\cdot$ km $^{-1}$,
38 $P=0.41$) or flat run training (1.21 ± 0.13 vs 1.19 ± 0.12 Kcal \cdot kg $^{-1}\cdot$ km $^{-1}$). Moreover, no changes in
39 E_C during downhill running were observed in either condition ($P>0.23$). vLTP increased
40 following both downhill (16.5 ± 0.7 vs 16.9 ± 0.6 km \cdot h $^{-1}$, $P=0.05$) and flat run training (16.9 ± 0.7
41 vs 17.2 ± 1.0 km \cdot h $^{-1}$, $P=0.05$), though no differences in responses were observed between groups
42 ($P=0.53$). Therefore, a short programme of supplementary downhill run training does not
43 appear to enhance running economy in already well-trained individuals.

44

45

46

47

48 **Key words:** Athletes, Athletic performance, energy cost, exercise training

49

50

51

52 **Introduction**

53 For distance running, maximal oxygen uptake ($\dot{V}O_{2max}$), the proportion of $\dot{V}O_{2max}$ that can be
54 sustained prior to the onset blood lactate accumulation (lactate thresholds) and running
55 economy (RE) are the primary physiological factors that underpin performance (Ingham et al.
56 2008). In populations where the differences in athletic capabilities are small, the combination
57 of RE and maximal oxygen uptake ($\dot{V}O_{2max}$) can account for >90% of the variability in
58 performance (McLaughlin, Howley, Bassett, Thompson, & Fitzhugh, 2010). However,
59 improvements in $\dot{V}O_{2max}$ for athletes with already high capacities can be difficult to achieve
60 (Hopker, Coleman, & Passfield, 2009; Iaia et al., 2009; Jones, 2006), therefore methods to
61 enhance RE are sought after to maximise an athlete's performance. Yet, established training
62 interventions that can improve RE in already well trained runners are limited.

63 Previous investigations have explored the use of strength/plyometric training to enhance RE in
64 trained distance runners. The addition of lower-limb strength and/or plyometric training to
65 endurance running programmes for ~10 weeks, has been noted to stimulate improvements in
66 RE of 4-8% (Johnston, Timothy, Kertzer, & Vroman, 1997; Paavolainen, Hakkinen,
67 Hamalainen, Nummela, & Rusko, 1999; Saunders et al., 2006; Sedano, Marín, Cuadrado, &
68 Redondo, 2013). It has been speculated that such training methods promote neuromuscular
69 adaptations, namely an increase muscle-tendon stiffness, that facilitate greater exploitation of
70 the stretch shortening cycle (SSC), in addition to improved running mechanics (Paavolainen
71 et al., 1999; Saunders et al., 2006). Downhill running might facilitate a more pronounced SSC
72 stimulus above habitual/flat running, and thus promote adaptations in SSC function, running
73 mechanics and economy.

74 Downhill running involves lowering the centre of mass within a stride cycle, releasing
75 gravitational potential energy. When compared to flat or uphill running, downhill running is
76 associated with greater impact loads and higher vertical velocity on landing (Gottschall &
77 Kram, 2005; Neves, Johnson, Hunter, & Myrer, 2014), resulting in greater eccentric
78 contractions of the extensor muscles of the lower limbs. Consequently, there is greater potential
79 for elastic energy storage and return (Snyder & Farley, 2011). Frequent exposure to these
80 higher impact loads and exaggerated stretch-shortening cycle activity could induce a range of
81 neural, physiological and mechanical adaptations that promotes more effective energy storage
82 and return. In addition, running downhill incurs a lower metabolic cost compared to flat or
83 uphill running (Margaria, Cerretelli, Aghemo, & Sassi, 1963), such that higher velocities can

84 be achieved for the same E_c and a greater volume of training at higher speeds may be possible
85 with downhill running compared to running on the flat. Consequently, downhill running
86 appears to involve an exaggerated SSC stimulus, from both the downhill gradient and higher
87 velocities, whilst also facilitating greater exposure compared to running on the flat, and
88 therefore might benefit running mechanics and economy.

89 To our knowledge, no previous investigation has examined the physiological responses to
90 extended periods of downhill run training. A one off bout of running down steep gradients (-
91 12-15%) has been shown to cause severe exercise induced muscle damage (EIMD) that has
92 been associated with a transient worsening of RE (Baumann et al., 2014; Chen, Nosaka, Lin,
93 Chen, & Wu, 2009). However, the use of shallow gradients and a progressive exposure
94 (LaStayo, Pierotti, Pifer, Hoppeler, & Lindstedt, 2000) would be expected to circumvent any
95 EIMD. Therefore, the aim of the current investigation was to assess the efficacy of a
96 supplementary 8 week programme (16 training sessions) of progressive downhill running as a
97 means of enhancing RE in well trained distance runners. The downhill running intervention
98 was compared to an equivalent supplementary 8-week programme of intensity matched flat
99 running to isolate the effect of surface gradient. It was hypothesised that prescribed regular
100 downhill running would improve RE compared to running on the flat.

101

102 **Methods**

103 **Participants**

104 Nineteen highly trained athletes (males, $n=17$; Age: 25 ± 6 years; stature: 179 ± 5 cm; body mass:
105 68.2 ± 7.2 kg; $\dot{V}O_{2max}$: 73.9 ± 5.5 mL \cdot kg $^{-1}\cdot$ min $^{-1}$; females $n=2$; Age: 24 ± 5 years, stature: 168 ± 4
106 cm, body mass: 58.3 ± 6.6 kg, $\dot{V}O_{2max}$: 62.6 ± 1.4 mL \cdot kg $^{-1}\cdot$ min $^{-1}$) completed the current
107 investigation. Participants' best performance times over the preceding two seasons were $118 \pm$
108 6% of the current British record as of May 2015 in their primary event between 800m and
109 marathon, equating to an IAAF points score of 773 ± 140 (Spiriev 2017). All participants were
110 treadmill habituated, and provided written informed consent prior to participating in this study
111 that had Loughborough University Ethics committee approval.

112 **Overview**

113 Participants were required to visit the laboratory on two occasions per week for 11 consecutive
114 weeks (Figure 1). Prior to the initial visits, participants provided an overview of their 'typical'
115 weekly training in the lead up to the investigation, that was categorised based on exercise
116 intensity in accordance with previous investigations (Seiler & Kjerland, 2006) (Table 1).

117 All participants performed 1-2 gym-based conditioning session per week as part of their
118 habitual training. Participants were pair matched (habitual training, competitive distances and
119 sex), and randomly allocated to the flat (n=9) or the downhill (n=10) groups. During week 1,
120 participants completed a submaximal flat running assessment followed by a maximal running
121 assessment, with ~15 minutes of rest in between, and returned to complete a submaximal
122 downhill running assessment. Participants then completed two blocks of 4 weeks of
123 supplementary flat (1%) or downhill (-5%) run training (outlined below), interspersed with a
124 week to complete submaximal running assessments to reassess appropriate training speeds.
125 Finally, participants returned to complete post training assessments in an identical format to
126 pre-training. Participants wore appropriate clothing and racing shoes, and with laboratory
127 conditions remaining consistent throughout all sessions (temperature, $19 \pm 1^{\circ}\text{C}$; relative
128 humidity, $43 \pm 12\%$).

129 **Protocol**

130 *Submaximal running assessments*

131 Prior to submaximal running assessments, body mass was measured using digital scales to the
132 nearest 0.1 kg. Stature was recorded to the nearest 1 cm using a stadiometer. Using calibrated
133 callipers (Harpenden, Holtain Limited, UK), body composition was assessed at pre- and post-
134 intervention using an 8 site skinfold method (bicep, tricep, subscapular, iliac crest, supra-iliac,
135 abdomen, thigh and calf). The total of the 8 sites was then calculated and used as an index of
136 fat mass.

137 Following a warm-up (~10 min at $10\text{-}12 \text{ km}\cdot\text{h}^{-1}$), participants completed a discontinuous
138 submaximal incremental test consisting of six to nine stages of 3 minutes continuous running,
139 with increments of $1 \text{ km}\cdot\text{h}^{-1}$ on a motorised treadmill of known belt speeds (HP cosmos Saturn,
140 Traunstein, Germany), as has been shown to produce reliable assessments of RE (Shaw,
141 Ingham, Fudge, & Folland, 2013). During downhill running assessments, the same procedure

142 was followed with the treadmill belt maintained at -5%. Runners ran with their self-selected
143 running style during all downhill training and testing. Breath-by-breath gas exchange data were
144 quantified via an automated open circuit metabolic cart throughout the running assessments
145 (Oxycon Pro, Carefusion, San Diego, USA), calibrated according to the manufacturers
146 guidelines. A photoelectric cell system (Optojump, Microgate, Bolzano, Italy) was used to
147 measure ground contact time, flight time, stride length and stride frequency over the final 60s
148 of submaximal running at 16 km·h⁻¹ during flat and downhill running, both pre and post the
149 interventions, as these variables have recently been related to RE and performance in a large
150 cohort of runners (Black, Handsaker, Allen, Forrester, & Folland, 2017). Due to equipment
151 limitations, observations were restricted to 12 athletes during flat assessments (downhill
152 training group, n=7; flat training group, n=5) and 11 athletes during downhill assessments
153 (downhill training group, n=7; flat training group, n=4). Between submaximal running stages
154 20µL of capillary blood was sampled from the earlobe for analysis of blood lactate (Biosen C-
155 line, EKF diagnostics, Germany). The velocity at lactate turnpoint vLTP was identified based
156 on the Thoden model (Thoden, 1991). The utilisation of $\dot{V}O_{2max}$ at vLTP (% $\dot{V}O_{2max}$), was
157 calculated by expressing $\dot{V}O_2$ at vLTP as a percentage of $\dot{V}O_{2max}$ (see below). The four stages
158 prior to vLTP were identified for each participant during flat (vLTP_F) and downhill running
159 (vLTP_D), with an average of these four stages used to quantify energy cost (E_C) for both flat
160 (RE_F) and downhill running (RE_D) in accordance with procedures outlined in previous studies
161 (Shaw, Ingham, & Folland, 2014).

162 Training velocities were based on vLTP, as this speed represents the highest speed where valid
163 measures of RE are still achievable. The vLTP from baseline flat and downhill assessments
164 were used to infer appropriate training velocities for the flat and downhill conditions,
165 respectively, during the first training block, with the vLTP from the mid-assessment used to
166 infer training paces during the second training block.

167 *Maximal running assessments*

168 $\dot{V}O_{2max}$ was determined by a continuous incremental treadmill running ramp test to volitional
169 exhaustion. Participants initially ran at a speed 2 km·h⁻¹ below the final speed of the
170 submaximal test and at a 1% gradient. Each minute, the incline was increased by 1% until
171 volitional exhaustion. The test duration was typically 6-8 minutes. $\dot{V}O_{2max}$ was defined as the
172 highest average breath-by-breath $\dot{V}O_2$ over a continuous 30s sample during the maximal
173 running assessment, expressed relative to body mass (mL·kg⁻¹·min⁻¹). The regression equation

174 describing the $\dot{V}O_2$ and speed relationship during the submaximal flat running assessment was
175 used to calculate the velocity associated with $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$).

176 *Supplementary training interventions*

177 Two progressive 'tempo' training sessions were included in athlete's weekly training (Figure
178 1), typically replacing an existing session of a similar intensity. During the first session,
179 following a warm up (~10 mins at ~11-12 km·h⁻¹), participants completed 7 min of running at
180 90% of the gradient specific vLTP, followed continuously by 5 mins at 100% vLTP.
181 Participants then rested for 3 min, followed by a final 3 min at 110% vLTP. The same session
182 was then repeated within 7 days, with volume incrementally increasing for each additional
183 week. For the following 3 weeks, 2 min were added to each intensity (i.e. by week 4: 13 min
184 at 90% vLTP, 11 min at 100% vLTP and 9 min at 110% vLTP). To ensure athletes could achieve
185 the total duration prescribed at 110%vLTP this period was divided into intervals that were ≤ 3
186 min with 90s rest between intervals (i.e. 7 min spilt into 3 x 2 min 20 second intervals, 9 min
187 into 3 x 3min intervals). During the second 4-week block the duration at each intensity was
188 only increased by 1 min·week⁻¹. As a result, the final two training sessions involved 17 min at
189 90% vLTP, 15 min at 100% vLTP and 13 min (5 x 2 min 36 s) at 110% vLTP. All
190 supplementary training sessions were supervised by the principle investigator.

191 **Statistical analyses**

192 Data analysis was conducted using SPSS (v21; IBM Corporation, Armonk, NY). Normal
193 distribution of the dependent variables was confirmed via Shapiro-wilk tests. Paired sample t-
194 tests were used to assess any differences between groups at baseline for the training,
195 anthropometrical, physiological and stride characteristics assessed. Within group changes in
196 physiological variables and stride parameters were assessed via paired samples t-tests. Between
197 group effects were assessed with mixed measures ANOVA (Group; downhill vs flat training ×
198 Time; Pre vs Post). Data are presented as mean ± SD, with significance differences accepted
199 at $P \leq 0.05$.

200 **Results**

201 The training groups were well matched, with no differences observed in age (27±6 and 23±5
202 yrs) or stature (177±5 and 179±5cm), nor were any differences noted in other anthropometrical,
203 training, physiological or biomechanical characteristics (Table 1; Table 2). Body mass

204 remained consistent across the study period for both flat and downhill groups ($P>0.10$).
205 Skinfolds decreased after flat training ($P=0.05$), but did not change in the downhill group
206 ($P=0.14$). However, no time x group interaction occurred ($P=0.48$).

207 **Flat running assessments**

208 RE_F demonstrated no within group changes after downhill ($P=0.41$) or flat training ($P=0.68$),
209 with no group x time interaction effect (ANOVA, $P=0.89$; Figure 2). $vLTP_F$ increased after the
210 flat ($P=0.05$) and downhill training ($P=0.05$), however no interaction effect was present (Table
211 3). When running at $vLTP$ an increase in $\% \dot{V}O_{2max}$ was evident when groups were combined
212 (ANOVA, main effect of time, $P=0.05$), however no interaction effect was present. Further, no
213 within group changes were evident in $\% \dot{V}O_{2max}$ at $vLTP$ after downhill ($86.2 \pm 8.0\%$ vs
214 $89.4 \pm 7.8\%$, $P=0.19$) or flat training ($86.5 \pm 4.5\%$ vs $89.1 \pm 4.5\%$, $P=0.11$). No differences in
215 $\dot{V}O_{2max}$ or $v\dot{V}O_{2max}$ were noted between pre and post assessments in either condition (Table 3),
216 nor were any group x time interaction effects present ($P=0.38$ and $P=0.55$).

217 Flight time, stride length and stride frequency remained unchanged between pre to post
218 assessments (Table 3). ANOVA revealed a significant group x time interaction effect for
219 ground contact time. However, post hoc analysis revealed no differences in contact time
220 between groups pre and post intervention ($P=0.64$) and within group t-tests showing contact
221 time displayed a non-significant increase in the flat training group ($P=0.09$) and a non-
222 significant decrease in the downhill training group ($P=0.18$) post training.

223 **Downhill running assessments**

224 RE_D showed no within group changes after downhill ($P=0.23$) or flat training ($P=0.87$), with
225 no interaction effect (ANOVA, $P=0.61$; Figure 2). $vLTP_D$ increased after downhill ($P=0.02$)
226 and flat training ($P=0.04$), however no interaction effect was present (Table 3). Moreover,
227 the $\% \dot{V}O_{2max}$ at $vLTP$ remained consistent for both the downhill ($82.5 \pm 7.9\%$ vs $85.3 \pm 6.9\%$,
228 $P=0.21$) and flat training groups ($82.7 \pm 5.2\%$ vs $84.4 \pm 3.6\%$, $P=0.43$) when running downhill.
229 Flight time, stride frequency, stride length and ground contact time remained unchanged during

230 downhill running assessments following training in both groups ($P>0.11$), with no group x time
231 interactions (Table 3).

232 **Discussion**

233 The aim of the current investigation was to evaluate the efficacy of a supplementary downhill
234 run training programme as a means to enhance the RE of well-trained distance runners. We
235 found that 8 weeks of supplementary downhill or flat run training at vLTP did not change RE.
236 Both training groups showed improvements in vLTP of both flat and downhill running, and
237 therefore these improvements were not specific to the training gradient. Contrary to our
238 hypothesis, a short programme of supplementary downhill run training did not enhance RE in
239 already well-trained individuals.

240 The influence of chronic downhill training on RE has not previously been documented. It was
241 proposed that downhill running could facilitate greater training time at high running velocities
242 involving prolonged exposure to high impact forces and an exaggerated SSC, potentially
243 leading to adaptations in SSC function, running mechanics and economy. Due to the reduced
244 E_C for a given exercise intensity, training velocities were $\sim 2 \text{ km}\cdot\text{h}^{-1}$ greater in the downhill
245 group compared to the flat training group. However, despite the exposure to the higher running
246 velocities and greater impact forces of downhill running, no changes in RE were observed after
247 the 16 sessions of downhill run training in already well-trained individuals. It is possible that,
248 the distinct biomechanical characteristics of downhill running, particularly the higher braking
249 forces and decreased propulsive forces (Gottschall & Kram, 2005) may have produced specific
250 neuromechanical adaptations that did not transfer to level running.

251 In contrast, traditional plyometric training has been shown to increase RE in trained endurance
252 athletes over a similar time frame (Paavolainen et al., 1999; Saunders et al., 2006), attributed
253 to concurrent changes in surrogate measures of neuromuscular adaptations (i.e. ground contact
254 times, 5 jump plyometric test performances) that might suggest a greater exploitation of the
255 SSC. In contrast, in the current study there were no changes in running mechanics following
256 downhill run training. The SSC that occurs during downhill running is likely less pronounced
257 and slower than the SSC during traditional plyometric exercises. Specifically, a short
258 amortization/transition phase between eccentric and concentric activity is widely considered
259 optimal to subsequent concentric force generation (Wilson et al. 1991). It is possible that the
260 SSC during downhill running involves a relatively long amortization phase with little

261 enhancement of subsequent concentric force production and thus may be a relatively weak
262 stimulus for SSC improvements.

263 The highly trained status of the current cohort could also, in part, explain the lack of change in
264 RE in the current investigation. Despite no previous exposure to structured downhill running,
265 participants all performed high intensity training and resistance based conditioning sessions in
266 their habitual training; matching previous observations from high performance endurance
267 runners (Esteve-Lanao, Juan, Earnest, Foster, & Lucia, 2005; Ingham, Fudge, & Pringle, 2012).
268 In contrast, previous investigations reporting an enhanced RE to short term strength/resistance
269 training interventions have commonly observed athletes with minimal resistance training
270 experience (Guglielmo, Greco, & Denadai, 2009; Saunders et al., 2006; Taipale, Mikkola,
271 Vesterinen, Nummela, & Häkkinen, 2013), or following extended periods (> 6 weeks) of no
272 resistance training (Johnston et al., 1997). Consequently, the changes in RE reported could
273 reflect the rapid neural adaptations and learning effect that occur in response to initial bouts of
274 resistance training in unaccustomed athletes (Folland & Williams, 2007). Indeed, when
275 additional strength and/or plyometric training has been incorporated into the training
276 programmes of resistance trained endurance athletes, no change or small improvements (~3%)
277 in RE have been reported after comparably long exposures of 12-14 weeks (Millet, Jaouen,
278 Borrani, & Candau, 2002; Sedano et al., 2013). Though changes did not reach significance in
279 the current study, the group response to downhill training was a 1.5% increase in RE, which is
280 comparable to the smallest worthwhile change in this variable (Shaw et al., 2013) - the
281 threshold for when a change is viewed as meaningful. It is therefore plausible that the short-
282 term intervention with a comparatively modest downhill running stimulus was insufficient to
283 promote any additional neuromuscular adaptations beyond the habitual training of the current
284 cohort.

285 It has been proposed that an athlete's RE varies according to their competitive distance and
286 habitually training velocity (Daniels & Daniels, 1992; Jones & Carter, 2000). Consequently, it
287 could be argued that training at a prescribed velocity itself could provide an efficacious method
288 to enhance RE at that given velocity. However, in line with the downhill training group, no
289 change was observed in RE at speeds close to vLTP for athletes performing intensity matched
290 flat running. These findings support previous investigations where no improvement in RE at
291 vLTP was noted following prescribed training at vLTP in recreational (Yoshida et al., 1990)
292 and highly trained runners (Sjödín, Jacobs, & Svedenhag, 1982). Whilst it is possible that a
293 longer exposure could be required due to the highly trained status of the cohort, no changes in

294 RE at speeds close to vLTP have been observed across a competitive season in highly trained
295 runners, despite a notable training volume around this velocity (Galbraith, Hopker, Cardinale,
296 Cunniffe, & Passfield, 2014). Overall, our findings and several other studies suggest that
297 structured flat run training at speeds around vLTP does not improve RE in a velocity specific
298 manner in already well-trained athletes.

299 No changes in $\dot{V}O_{2max}$ were apparent following 8 weeks of training in either condition. These
300 findings are in accordance with previous observations from trained runners, where $\dot{V}O_{2max}$ has
301 remained consistent following the introduction of additional training of similar intensities: at
302 vLTP (Sjödín et al., 1982), and interval training at and above vLTP (Barnes, Hopkins,
303 McGuigan, & Kilding, 2013; Billat, Demarle, Paiva, & Koralsztein, 2002). As training at or
304 around $v\dot{V}O_{2max}$ has been postulated to be the most effective way to enhance $\dot{V}O_{2max}$ in well
305 trained athletes (Midgley, McNaughton, & Wilkinson, 2006), it seems likely that the
306 submaximal intensities of the current investigation were insufficient to prompt improvements.

307 In contrast, increases in both vLTP_F and vLTP_D were noted following the downhill (2.4 and
308 3.2%, respectively) and flat training (1.8 and 2.0%, respectively). These findings support
309 previous reports where enhancements in vLTP_F have been observed following the
310 incorporation of additional run training around vLTP in trained runners (Billat, Sirvent,
311 Lepretre, & Koralsztein, 2004; Sjödín et al., 1982). Furthermore the improvements at both test
312 gradients after training with both flat and downhill running indicates that these metabolic
313 adaptations in vLTP are not gradient dependant, and are likely mediated by changes in lactate
314 production (e.g. mitochondrial biogenesis and elevated oxidative enzyme concentrations /
315 activity (Holloszy & Coyle, 1984)) or removal.

316 It should be noted that the current study is not without limitation. Whilst a comprehensive
317 assessment of physiological parameters was conducted, there was no direct measure of
318 performance in either the downhill or flat condition. Though vLTP can provide an index of
319 submaximal performance capabilities, specifically 10km performances (Jones 2006), the
320 sensitivity of this measure could have limited the identification of group x time differences. In
321 addition, more detailed assessment of kinetic parameters such as ground reaction forces might
322 have facilitated a greater understanding of the kinetic alterations following the training period.
323 Therefore, future investigations might look to utilise instrumented treadmills or motion capture
324 systems to shed further light on the biomechanical responses to downhill run training.

325

326 **Conclusion**

327 In conclusion, our data indicate that 8 weeks of supplementary downhill run training at vLTP
328 within existing training programmes does not enhance the RE of already well-trained runners.
329 Given the importance of running economy to endurance performance, further investigations
330 are required to elucidate practical and accessible methods to enhance running economy in
331 already well-trained athletes.

332

333

334

335

336

337

338

339

340

341

342

343

344

345

346

347

348

349

350 **References**

- 351 Barnes, K. R., Hopkins, W. G., McGuigan, M. R., & Kilding, A. E. (2013). Effects of
352 different uphill interval-training programs on running economy and performance.
353 *International Journal of Sports Physiology and Performance*, 8(6), 639–647.
354 <https://doi.org/10.1016/j.jsams.2012.11.035>
- 355 Baumann, C. W., Green, M. S., Doyle, J. a, Rupp, J. C., Ingalls, C. P., & Corona, B. T.
356 (2014). Muscle injury after low-intensity downhill running reduces running economy.
357 *Journal of Strength and Conditioning Research / National Strength & Conditioning*
358 *Association*, 28, 1212–1218. <https://doi.org/10.1519/JSC.0000000000000422>
- 359 Billat, V., Demarle, a, Paiva, M., & Koralsztein, J. P. (2002). Effect of training on the
360 physiological factors of performance in elite marathon runners (males and females).
361 *International Journal of Sports Medicine*, 23(5), 336–41. [https://doi.org/10.1055/s-](https://doi.org/10.1055/s-2002-33265)
362 [2002-33265](https://doi.org/10.1055/s-2002-33265)
- 363 Billat, V., Sirvent, P., Lepretre, P., & Koralsztein, J. (2004). Training effect on performance,
364 substrate balance and blood lactate concentration at maximal lactate steady state in
365 master endurance-runners. *European Journal of Physiology*, 447(6), 875–883.
366 <https://doi.org/10.1007/s00424-003-1215-8>
- 367 Black, M. I., Handsaker, J. C., Allen, S. J., Forrester, S. E., & Folland, J. P. (2017). Is There
368 an Optimum Speed for Economical Running? *International Journal of Sports*
369 *Physiology and Performance*, 44(0), 1–23. <https://doi.org/10.1123/ijsp.2017-0015>
- 370 Chen, T. C., Nosaka, K., Lin, M.-J., Chen, H.-L., & Wu, C.-J. (2009). Changes in running
371 economy at different intensities following downhill running. *Journal of Sports Sciences*,
372 27(11), 1137–44. <https://doi.org/10.1080/02640410903062027>
- 373 Daniels, J., & Daniels, N. (1992). Running economy of elite male and elite female runners.
374 *Medicine and Science in Sports and Exercise*, 24, 483–9.
- 375 di Prampero, P. (2003). Factors limiting maximal performance in humans. *European Journal*
376 *of Applied Physiology*, 90(3–4), 420–429. <https://doi.org/10.1007/s00421-003-0926-z>
- 377 Esteve-Lanao, J., Juan, A., Earnest, C., Foster, C., & Lucia, A. (2005). How Do Endurance
378 Runners Actually Train? Relationship with Competition Performance. *Medicine &*
379 *Science in Sports & Exercise*, 37(3), 496–504.
380 <https://doi.org/10.1249/01.MSS.0000155393.78744.86>
- 381 Folland, J. P., & Williams, A. G. (2007). The Adaptations to Strength Training Increased
382 Strength. *Sports Medicine*, 37(2), 145–168. [https://doi.org/10.2165/00007256-](https://doi.org/10.2165/00007256-200737020-00004)
383 [200737020-00004](https://doi.org/10.2165/00007256-200737020-00004)
- 384 Galbraith, A., Hopker, J., Cardinale, M., Cunniffe, B., & Passfield, L. (2014). A 1-year study
385 of endurance runners: training, laboratory tests, and field tests. *International Journal of*
386 *Sports Physiology and Performance*, 9(6), 1019–1025.
387 <https://doi.org/10.1123/ijsp.2013-0508>
- 388 Gottschall, J. S., & Kram, R. (2005). Ground reaction forces during downhill and uphill
389 running. *Journal of Biomechanics*, 38(3), 445–52.
390 <https://doi.org/10.1016/j.jbiomech.2004.04.023>

- 391 Guglielmo, L., Greco, C., & Denadai, B. (2009). Effects of Strength Training on Running
392 Economy. *International Journal of Sports Medicine*, 30(1), 27–32.
393 <https://doi.org/10.1055/s-2008-1038792>
- 394 Holloszy, J. O., & Coyle, E. F. (1984). Adaptations of skeletal muscle to endurance exercise
395 and their metabolic consequences. *Journal of Applied Physiology: Respiratory,
396 Environmental and Exercise Physiology*, 56(4), 831–8. Retrieved from
397 <http://www.ncbi.nlm.nih.gov/pubmed/6373687>
- 398 Hopker, J., Coleman, D., & Passfield, L. (2009). Changes in cycling efficiency during a
399 competitive season. *Medicine and Science in Sports and Exercise*, 41(4), 912–9.
400 <https://doi.org/10.1249/MSS.0b013e31818f2ab2>
- 401 Iaia, F., Hellsten, Y., Nielsen, J., Fernstrom, M., Sahlim, K., & Bangsbo, J. (2009). Four
402 weeks of speed endurance training reduces energy expenditure during exercise and
403 maintains muscle oxidative capacity despite a reduction in training volume. *Journal of
404 Applied Physiology*, 106, 73–80. <https://doi.org/10.1152/jappphysiol.90676.2008>.
- 405 Ingham, S., Fudge, B., & Pringle, J. (2012). Training Distribution , Physiological Profile ,
406 and Performance for a Male International 1500-m Runner. *International Journal of
407 Sports Physiology and Performance*, 7(2), 193–195. Retrieved from
408 <http://www.ncbi.nlm.nih.gov/pubmed/22634971>
- 409 Ingham, S., Whyte, G., Pedlar, C., Bailey, D., Dunman, N., & Nevill, A. (2008).
410 Determinants of 800-m and 1500-m running performance using allometric models.
411 *Medicine and Science in Sports and Exercise*, 40(2), 345–50.
412 <https://doi.org/10.1249/mss.0b013e31815a83dc>
- 413 Johnston, R., Timothy, J., Kertzer, R., & Vroman, N. (1997). Strength training in female
414 distance runners: Impact on running economy. *Journal of Strength and Conditioning
415 Research*, 11(4), 224–229.
- 416 Jones, A. M. (2006). The Physiology of the World Record Holder for the Women’s
417 Marathon. *International Journal of Sports Science and Coaching*, 1(2), 101–116.
418 <https://doi.org/10.1260/174795406777641258>
- 419 Jones, A. M., & Carter, H. (2000). The effect of endurance training on parameters of aerobic
420 fitness. *Sports Medicine*, 29(6), 373–86. Retrieved from
421 <http://www.ncbi.nlm.nih.gov/pubmed/10870864>
- 422 LaStayo, P. C., Pierotti, D. J., Pifer, J., Hoppeler, H., & Lindstedt, S. L. (2000). Eccentric
423 ergometry: increases in locomotor muscle size and strength at low training intensities.
424 *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*,
425 278, R1282–R1288.
- 426 Margaria, R., Cerretelli, P., Aghemo, P., & Sassi, G. (1963). Energy cost of running. *Journal
427 of Applied Physiology*, 18, 367–70.
- 428 McLaughlin, J. E., Howley, E. T., Bassett, D. R., Thompson, D. L., & Fitzhugh, E. C. (2010).
429 Test of the classic model for predicting endurance running performance. *Medicine and
430 Science in Sports and Exercise*, 42(5), 991–7.
431 <https://doi.org/10.1249/MSS.0b013e3181c0669d>

- 432 Midgley, A., McNaughton, L., & Wilkinson, M. (2006). Is there an optimal training intensity
433 for enhancing the maximal oxygen uptake of distance runners?: empirical research
434 findings, current opinions, physiological rationale. *Sports Medicine*, 36(2), 117–132.
435 Retrieved from
436 <http://www.ingentaconnect.com/content/adis/smd/2006/00000036/00000002/art00003>
- 437 Millet, G. P., Jaouen, B., Borrani, F., & Candau, R. (2002). Effects of concurrent endurance
438 and strength training on running economy and $\dot{V}O_2$ kinetics. *Medicine and Science in
439 Sports and Exercise*, 34(8), 1351–1359.
- 440 Neves, K. A., Johnson, a. W., Hunter, I., & Myrer, J. W. (2014). Does achilles tendon cross
441 sectional area differ after downhill, level and uphill running in trained runners? *Journal
442 of Sports Science & Medicine*, 13(4), 823–828. Retrieved from
443 <http://www.ncbi.nlm.nih.gov/pubmed/25435775>
- 444 Paavolainen, L., Hakkinen, K., Hamalainen, I., Nummela, A., & Rusko, H. (1999).
445 Explosive-strength training improves 5-km running time by improving running economy
446 and muscle power. *Journal of Applied Physiology*, 86(5), 1527–1533. Retrieved from
447 <http://jap.physiology.org/content/86/5/1527.short>
- 448 Saunders, P., Telford, R., Pyne, D., Peltola, E., Cunningham, R., Gore, C., & Hawley, J.
449 (2006). Short-term plyometric training improves running economy in highly trained
450 middle and long distance runners. *The Journal of Strength and Conditioning Research*,
451 20(4), 947–954. Retrieved from [http://journals.lww.com/nsca-
452 jscr/abstract/2006/11000/short_term_plyometric_training_improves_running.36.aspx](http://journals.lww.com/nsca-jscr/abstract/2006/11000/short_term_plyometric_training_improves_running.36.aspx)
- 453 Sedano, S., Marín, P. J., Cuadrado, G., & Redondo, J. C. (2013). *Concurrent Training in
454 Elite Male Runners. Journal of Strength and Conditioning Research* (Vol. 27).
455 <https://doi.org/10.1519/JSC.0b013e318280cc26>
- 456 Seiler, K. S., & Kjerland, G. Ø. (2006). Quantifying training intensity distribution in elite
457 endurance athletes: is there evidence for an “optimal” distribution? *Scandinavian
458 Journal of Medicine & Science in Sports*, 16(1), 49–56. [https://doi.org/10.1111/j.1600-
459 0838.2004.00418.x](https://doi.org/10.1111/j.1600-0838.2004.00418.x)
- 460 Shaw, A. J., Ingham, S. A., Fudge, B. W., & Folland, J. P. (2013). The reliability of running
461 economy expressed as oxygen cost and energy cost in trained distance runners. *Applied
462 Physiology, Nutrition, and Metabolism = Physiologie Appliquée, Nutrition et
463 Métabolisme*, 38(12), 1268–72. <https://doi.org/10.1139/apnm-2013-0055>
- 464 Shaw, A. J., Ingham, S. a, & Folland, J. P. (2014). The valid measurement of running
465 economy in runners. *Medicine and Science in Sports and Exercise*, 46(10), 1968–73.
466 <https://doi.org/10.1249/MSS.0000000000000311>
- 467 Sjödín, B., Jacobs, I., & Svedenhag, J. (1982). Changes in onset of blood lactate
468 accumulation (OBLA) and muscle enzymes after training at OBLA. *European Journal
469 of Applied Physiology*, 49, 45–57. Retrieved from
470 <http://www.springerlink.com/index/X6U44242H558W778.pdf>
- 471 Spiriev B. (2017) IAAF scoring tables of athletics, 2017 revised additon. IAAF..
- 472 Snyder, K. L., & Farley, C. T. (2011). Energetically optimal stride frequency in running: the
473 effects of incline and decline. *The Journal of Experimental Biology*, 214(Pt 12), 2089–

474 95. <https://doi.org/10.1242/jeb.053157>

475 Taipale, R. S., Mikkola, J., Vesterinen, V., Nummela, a., & Häkkinen, K. (2013).
476 Neuromuscular adaptations during combined strength and endurance training in
477 endurance runners: maximal versus explosive strength training or a mix of both.
478 *European Journal of Applied Physiology*, 113(2), 325–335.
479 <https://doi.org/10.1007/s00421-012-2440-7>

480 Thoden, J. (1991). Testing aerobic power. In J. MacDougall, H. Wenger, & H. Green (Eds.),
481 *Physiological Testing of the High-Performance Athlete* (pp. 107–173). Champaign, IL:
482 Human Kinetics.

483 Wilson GJ, Wood GA, Elliott BC. (1991). Optimal stiffness of series elastic component in a
484 stretch-shorten cycle activity. *Journal of Applied Physiology*, 70(2), 825-33.

485
486 Yoshida, T., Udo, M., Chida, M., Ichioka, M., Makiguchi, K., & Yamaguchi, T. (1990).
487 Applied Physiology distance runners and competitive walkers. *European Journal of*
488 *Applied Physiology*, 61, 197–201.

489

490

491

492

493

494

495

496

497

498

499

500

501

502

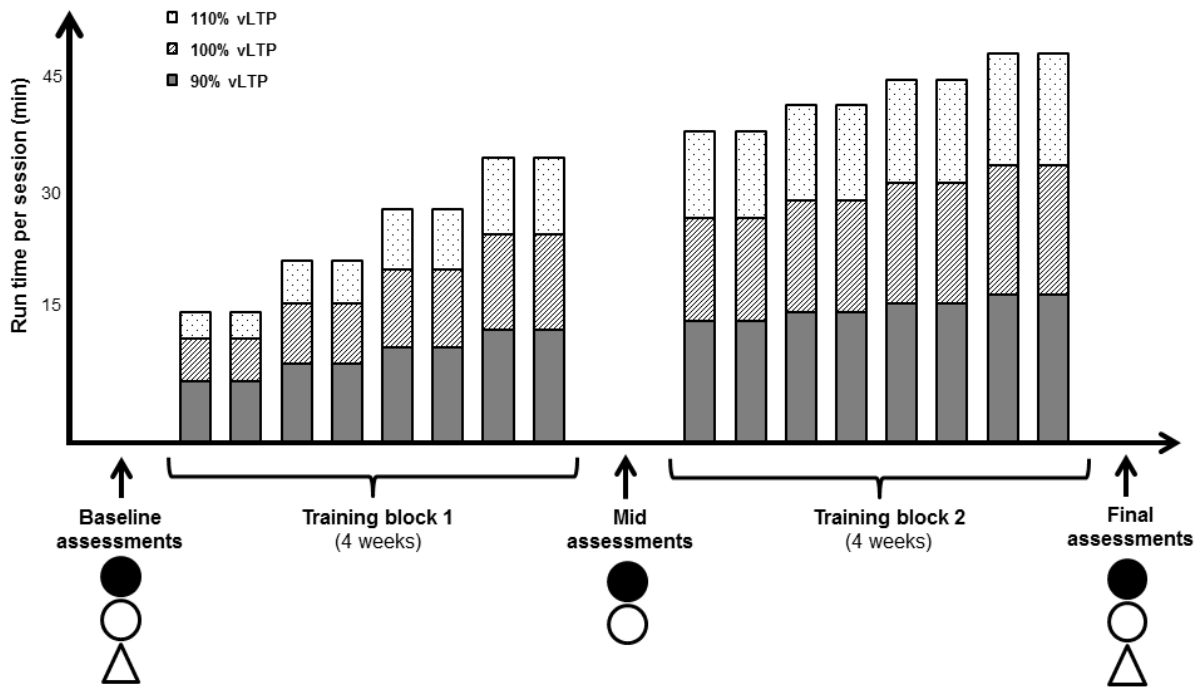
503

504

505

506

507



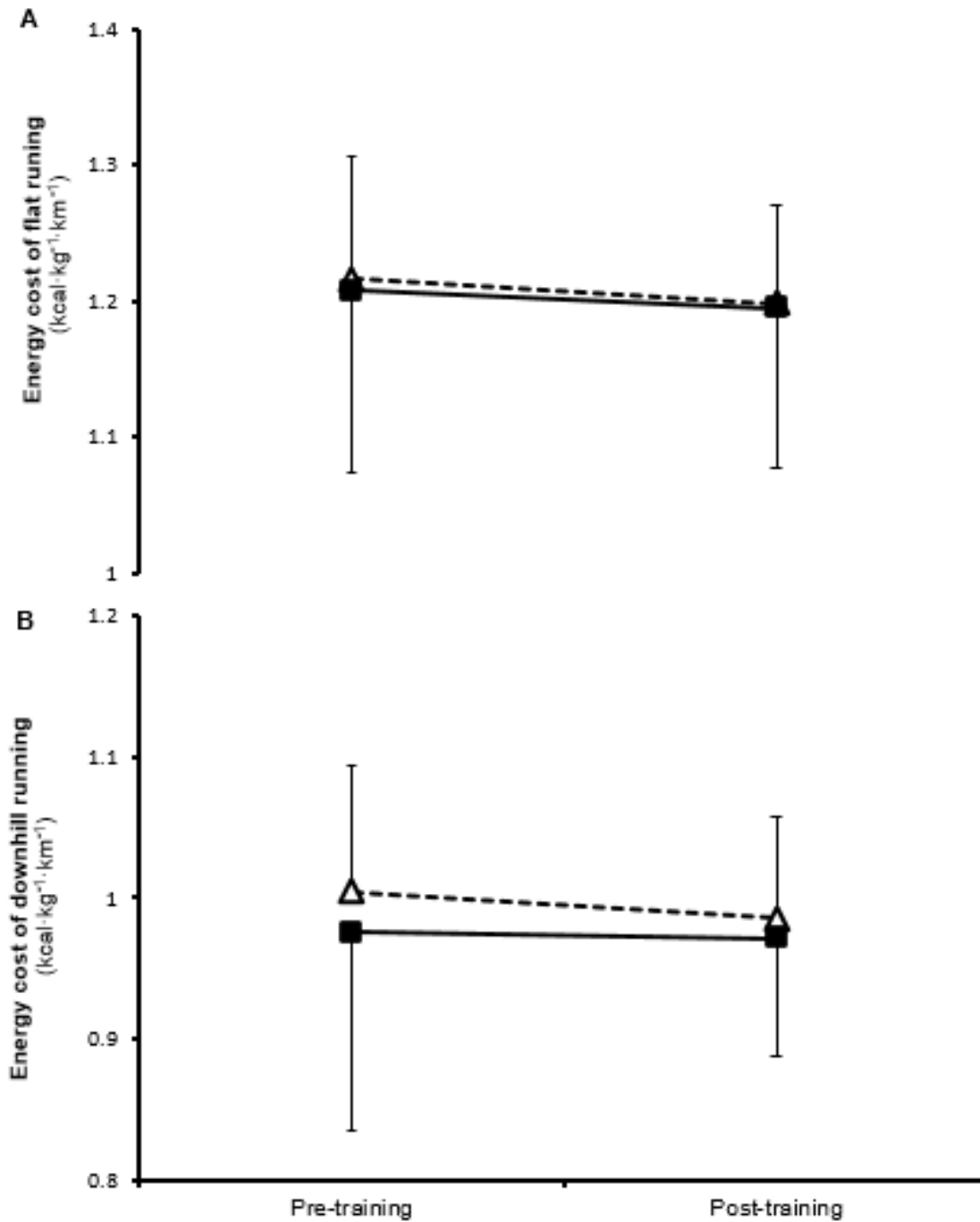
508

509

510

511 **Figure 1.** Schematic overview of the study. Bars represent running volume per training
 512 session, split into the 3 running intensities. Filled circles represent submaximal flat running
 513 assessments; Unfilled circles represent submaximal downhill running assessments; Unfilled
 514 triangles represent maximal running assessments.

515



516

517 **Figure 2.** Energy cost pre- and post-8 weeks of supplementary training in the flat (Solid
 518 squares, solid line) and downhill (Open triangles, dashed line) training groups during
 519 submaximal **A.** flat and **B.** downhill running assessments.

520

521

522

523

524 **Table 1.** Participant’s weekly run training prior to intervention, categorised by a 3 zone
525 approach (Seiler et al. 2006). Zone 1 < lactate threshold; Zone 2 > lactate threshold, < lactate
526 turnpoint; Zone 3 > lactate turnpoint.

Group	Total run volume (miles)	Zone 1 (% total volume)	Zone 2 (% total volume)	Zone 3 (% total volume)
Flat training	54.6 ± 5.2	69 ± 9	16 ± 10	15 ± 3
Downhill training	53.6 ± 7.6	68 ± 9	18 ± 10	14 ± 3

527

528

529

530

531

532

533

534

535

536

537

538

539

540

541

542

543

544

545

546 **Table 2.** Anthropometric and physiological variables assessed at baseline and post 8 weeks of
 547 prescribed training

	Flat training		Downhill training	
	<i>Pre</i>	<i>Post</i>	<i>Pre</i>	<i>Post</i>
Body mass (kg)	68.2 ± 7.9	67.2 ± 8.1	66.2 ± 7.7	66.1 ± 7.4
Skinfolds (mm)	55.0 ± 22.9	50 ± 17.9	48.6 ± 15.4	45.7 ± 10.9
$\dot{V}O_{2max}$ (mL·kg ⁻¹ ·min ⁻¹)	72.9 ± 6.7	72.6 ± 5.9	72.6 ± 6.7	70.7 ± 4.9
$v\dot{V}O_{2max}$ (km·h ⁻¹)	19.7 ± 1.6	19.5 ± 1.3	19.2 ± 1.3	19.1 ± 1.0

548 $\dot{V}O_{2max}$, maximal oxygen uptake; $v\dot{V}O_{2max}$, velocity associated with maximal oxygen uptake

549
 550
 551
 552
 553
 554
 555
 556
 557
 558
 559
 560
 561
 562
 563
 564
 565
 566

567 **Table 1.** Physiological and biomechanical variables assessed pre and post 8 weeks of prescribed training in the flat and downhill training groups.

568

	Flat training		Downhill training		ANOVA (group x time; P=)
	<i>Pre</i>	<i>Post</i>	<i>Pre</i>	<i>Post</i>	
<i>Flat Running</i>					
LTP _F (km·h ⁻¹)	16.9 ± 0.7	17.2 ± 1.0*	16.5 ± 0.7	16.9 ± 0.6*	0.53
Ground contact (s)	0.20 ± 0.02	0.21 ± 0.01	0.21 ± 0.01	0.20 ± 0.01	0.03
Stride length (m)	3.02 ± 0.21	3.07 ± 0.12	2.96 ± 0.12	3.01 ± 0.19	0.98
Stride frequency (Strides·min ⁻¹)	176 ± 14	174 ± 7	178 ± 7	179 ± 6	0.64
Flight time (s)	0.14 ± 0.02	0.14 ± 0.02	0.13 ± 0.02	0.13 ± 0.02	0.64
<i>Downhill Running</i>					
LTP _D (km·h ⁻¹)	19.3 ± 1.0	19.7 ± 1.3*	18.5 ± 0.8	19.1 ± 0.8*	0.53
Ground contact (s)	0.20 ± 0.02	0.21 ± 0.01	0.20 ± 0.02	0.20 ± 0.01	0.21
Stride length (m)	3.10 ± 0.20	3.18 ± 0.15	3.00 ± 0.05	3.05 ± 0.05	0.44
Stride frequency (Strides·min ⁻¹)	170 ± 12	169 ± 8	176 ± 4	177 ± 5	0.27
Flight time (s)	0.15 ± 0.02	0.15 ± 0.01	0.14 ± 0.02	0.14 ± 0.02	0.74

569 * - denotes significant difference to pre-assessment ($P \leq 0.05$). RE_D, downhill running economy; LTP_F, lactate threshold for flat running; LTP_D,
 570 lactate threshold for downhill running.

571