

28 **Efficacy of depth jumps to elicit a post-activation performance enhancement in junior**
29 **endurance runners**

31 **Abstract**

32
33 *Objectives:* To determine the effect of performing depth jumps (DJ) pre-exercise on running economy
34 (RE) and time to exhaustion (TTE) at the speed associated with maximal oxygen uptake ($s\dot{V}O_{2max}$) in a
35 group of high-performing junior middle-distance runners.

36 *Design:* Randomized crossover study.

37 *Methods:* Seventeen national- and international-standard male distance runners (17.6 ± 1.2 years, 63.4
38 ± 6.3 kg, 1.76 ± 0.06 m, 70.7 ± 5.2 ml \cdot kg $^{-1}\cdot$ min $^{-1}$) completed two trials. Following a 5 min warm-up at
39 60% $\dot{V}O_{2max}$, participants performed a 5 min run at 20% Δ below oxygen uptake corresponding with
40 lactate turn-point to determine pre-intervention RE. Participants then completed either six DJ from a
41 box equivalent to their best counter-movement jump (CMJ) or a control condition (C) involving body
42 weight quarter squats. After a 10 min passive recovery, another 5 min sub-maximal run was performed
43 followed by a run to exhaustion at $s\dot{V}O_{2max}$.

44 *Results:* Compared to the C trial, DJ produced moderate improvements (-3.7%, 95% confidence interval
45 for effect size: 0.25-1.09) in RE, which within the context of minimal detectable change is considered
46 possibly beneficial. Differences in TTE and other physiological variables were most likely trivial (ES:
47 <0.2). Individual responses were small, however a partial correlation revealed a moderate relationship
48 ($r=-0.55$, $p=0.028$) between change in RE and CMJ height.

49 *Conclusions:* The inclusion of a set of six DJ in the warm-up routine of a well-trained young male
50 middle-distance runner is likely to provide a moderate improvement in RE.

51
52
53 **Keywords:** warm-up, potentiation, pre-activation, running, physiology, plyometrics

54

55

56 **Abbreviations**

57 C = control condition

58 CI = confidence interval

59 CMJ = counter-movement jump

60 DJ = depth jumps

61 HR = heart rate

62 LTP = lactate turnpoint

63 MDC₉₅ = minimal detectable change (95% confidence)

64 MLC = myosin light chains

65 PAPE = post-activation performance enhancement

66 RE = running economy

67 sLTP = speed associated with lactate turnpoint

68 $s\dot{V}O_{2\max}$ = speed associated with $\dot{V}O_{2\max}$

69 TE = typical error

70 TTE = time to exhaustion

71

72

73

74 **Introduction**

75

76 Warm-up strategies for endurance athletes typically aim to achieve acute metabolic and cardiovascular
77 adjustments, which enhance the oxygen uptake ($\dot{V}O_2$) kinetic response¹. Distance running performance
78 is underpinned by several important physiological determinants, which are limited by metabolic and
79 cardiovascular factors, however neuromuscular characteristics also play an important role². It is
80 currently unknown whether high-intensity strength-based activities incorporated into a warm-up are
81 capable of acutely activating the neuromuscular system, thus providing additional benefits to the
82 determinants of performance in distance runners.

83

84 For short-duration athletic tasks, such as sprints and jumps, there is a large body of evidence
85 demonstrating possible improvements in performance 5-12 min after completion of a ballistic exercise
86 (e.g. plyometrics) or a heavy resistance exercise (>85% one repetition maximum)^{3,4}. This enhancement
87 of voluntary movement has been referred to as ‘post-activation performance enhancement’ (PAPE)⁵,
88 and can be explained by a number of physiological mechanisms. Most notably, acute enhancement in
89 voluntary movement have often been attributed to a ‘potentiation’ response, which increases myosin
90 light chains (MLC) phosphorylation, thereby enhancing rate of force development⁶. However, this
91 effect is short-lived (~5 min)⁷ and has rarely been observed during voluntary contractions. Other
92 unrelated physiological effects that may explain a PAPE include: an increase in muscle temperature⁸,
93 modulation of the H-reflex⁹, an increase in motor unit recruitment⁶, elevations in hormones¹⁰, and
94 changes in limb stiffness³. Although, some of these mechanisms have been shown to facilitate a short-
95 term improvement in explosive power performance, there has been recent speculation that endurance-
96 related outcomes may also benefit¹¹.

97

98 Improvements in RE and time-trial performance have been reported following a chronic strength
99 training intervention¹², however only a few studies have reported how these methods might acutely
100 enhance these parameters¹³⁻¹⁵. A series of sprints (6x10 s) wearing a weighted vest prior to an
101 incremental treadmill run has been shown to improve peak running speed and RE via changes in leg

102 stiffness, compared to a warm-up which included non-weighted sprints¹³. High-load resistance exercise
103 has also been shown to enhance 20 km time-trial performance in well-trained cyclists¹⁵. A similar
104 finding was observed in a group of elite rowers during a 1 km time trial, with power in the first 500 m
105 displaying improvement following a series of 5x5 s isometric contractions on the rowing ergometer¹⁴.
106 Both of these investigations^{14,15} attributed the improvements to a potentiation response. A PAPE is
107 transient, therefore selecting an appropriate recovery duration following a strength-based stimulus is
108 crucial to ensuring fatigue has dissipated sufficiently yet a post-activation state remains. A rest period
109 of 5-10 min following a set of voluntary contractions has been suggested for endurance athletes¹¹, and
110 the aforementioned studies in endurance runners¹³ and cyclists¹⁵ utilized a 10 min recovery.

111

112 Simple strategies incorporated into warm-up routines, which have the potential to improve
113 performance, are likely to be of considerable interest to athletes and their coaches. Chronic plyometric
114 training has been shown to enhance RE and performance¹² and plyometrics have been used to acutely
115 enhance sprint performance in athletically trained males¹⁶. Importantly, plyometrics do not require
116 specialist or cumbersome equipment and can be easily utilized in a field-based setting with athletes.
117 Based on the aforementioned information, we conjecture that a simple plyometric exercise would
118 improve RE and performance. Consequently, the aim of this study was to examine the influence of
119 performing depth jumps (DJ) on RE and TTE in a group of high-performing junior middle-distance
120 runners.

121

122 **Methods**

123

124 Following institution level ethical approval and in accordance with the Declaration of Helsinki, 17
125 junior male middle-distance runners of national and international standard took part in this study (Table
126 1). All participants were classified as post-pubertal (≥ 1 year) based upon a calculation of predicted
127 maturity offset¹⁷ and were free of injury. Participants (and parents/guardians for those <18 years) were
128 informed of the purpose of the investigation and thereafter provided written, informed consent to take
129 part.

130

131 ***Table 1 about here***

132

133 Participants attended the laboratory on three occasions, each separated by 2-7 days. Trials were
134 completed at the same time of day under similar conditions (barometric pressure: 750-770 mmHg,
135 temperature: 16.0-19.3°C, relative humidity: 30-43%) on a motorized treadmill (HP Cosmos Pulsar 4.0,
136 Cosmos Sports & Medical GmbH, Munich, Germany). Participants were requested to arrive in a
137 hydrated state, at least 2 h post-prandial and having not participated in any strenuous exercise in the
138 preceding 24 h.

139

140 The first testing session involved a discontinuous submaximal incremental running assessment followed
141 by a $\dot{V}O_{2\max}$ test with the treadmill gradient inclined to 1% throughout. Following a 5 min warm-up,
142 participants completed 5-7 bouts of running each lasting 3 min with 30 s passive rest to allow for a
143 capillary blood sample to be taken. The speed of the first stage was selected based upon the participants
144 best times and published recommendations¹⁸. Speed was subsequently increased by 1 km·h⁻¹ each stage
145 until lactate turn-point (LTP), defined as a rise in lactate of >1 mMol·L⁻¹ from the previous stage¹⁹, was
146 reached. Following a 5 min passive recovery, participants ran at the speed associated with their LTP
147 (sLTP) and every minute thereafter, the treadmill speed increased by 1 km·h⁻¹ until volitional
148 exhaustion. $\dot{V}O_{2\max}$ was defined as the highest 30 s mean $\dot{V}O_2$ value obtained during the $\dot{V}O_{2\max}$ test.
149 $s\dot{V}O_{2\max}$ was identified as the final speed achieved for >30 s during the assessment of $\dot{V}O_{2\max}$. After 20
150 min active recovery (slow walking), participants performed three maximum CMJs with hands placed
151 on hips on a force plate (Kistler 9287BA, Kistler Instruments Ltd, Hampshire, UK) sampling at 1000
152 Hz, with 90 s rest permitted between each attempt. Jump height was determined by calculating centre
153 of mass displacement from the participants take-off velocity. CMJ height was used to individualize box
154 height (to the nearest 0.01 m) for the DJ. Participants were then familiarized with the exercises to be
155 used in the two warm-up scenarios (DJ and C).

156

157 On the second and third visits to the laboratory, participants completed two performance trials in a
158 quasi-randomized counter-balanced order (ABBA method). One trial included a warm-up involving a
159 set of DJ and the other a control condition (C), involving unloaded quarter squats. The two trials
160 commenced with a warm-up at 60% $\dot{V}O_{2\max}$ followed by 5 min of running at a speed corresponding to
161 20% Δ below $\dot{V}O_2$ at LTP²⁰. The delta value represents the difference between $\dot{V}O_2$ at sLTP and $\dot{V}O_{2\max}$.
162 Speed was determined by deducting 20% of this delta value from $\dot{V}O_2$ at LTP and entering this value
163 into the linear regression equation for the speed- $\dot{V}O_2$ relationship for each participant. Following a 5
164 min passive recovery, participants completed six repetitions of either DJ or the C exercise. For the DJ,
165 participants placed their feet on the edge of the box, were instructed to step off a box whilst maintaining
166 an extended knee on the supporting leg, and rebound as high as possible whilst minimizing their ground
167 contact time. In the C trial, participants were instructed to descend into a shallow squat position (~140°
168 knee flexion) with heels remaining in contact with the ground, before slowly returning to standing. This
169 exercise was included to mask the active effect that was anticipated from the DJ and minimize the
170 likelihood of a placebo response. Both protocols were followed by a further 10 min of passive rest to
171 allow neuromuscular fatigue to dissipate but maximize the likelihood of a PAPE response being
172 realized. Immediately prior to remounting the treadmill, participants were asked to provide a rating (1-
173 10) of perceived readiness²¹. To evaluate the effect of the intervention on RE, participants then ran for
174 a further 5 min at 20% Δ below $\dot{V}O_2$ at LTP. This was followed by a 1 min rest and a run to exhaustion
175 at $s\dot{V}O_{2\max}$. Participants were blinded to the duration they had been running for throughout the trial.

176
177 At the start of each testing session, participant's body mass was taken using digital scales (MPMS-230,
178 Marsden Weighing Group, Oxfordshire, UK) to the nearest 0.1 kg. Stature and sitting height were also
179 measured with a stadiometer (SECA GmbH & Co., Hamburg, Germany) to the nearest 0.01 m for
180 prediction of maturity offset. A 20 μ L blood sample was taken from the earlobe at rest and the end of
181 every running stage across all testing sessions. Samples were hemolysed and subsequently analyzed for
182 blood lactate concentration (Biosen C-Line, EKF Diagnostic, Barleben, Germany). Gas exchange was
183 measured breath-by-breath via an automated open circuit metabolic cart (Oxycon Pro, Enrich Jaeger
184 GmbH, Hoechberg, Germany) calibrated to manufacturer's recommendations. Typical error (TE) of

185 measurement has previously been reported for RE using this system in junior distance runners (<2%)
186 and test-retest reliability is considered excellent (intra-class correlation coefficient: >0.9)¹⁹. Following
187 filtering of breath-by-breath data to remove errant breathes, oxygen consumption ($\dot{V}O_2$) and carbon
188 dioxide production ($\dot{V}CO_2$) were averaged for the final 2 min of both 5 min stages in the main trials and
189 were subsequently used to calculate RE in terms of energy cost using updated non-protein respiratory
190 quotients²². To verify a steady-state had been achieved, the difference between the first 60 s of the final
191 two minutes and the last 60 s was calculated. A difference smaller than the minimal detectable change
192 (MDC₉₅), calculated as TE of the mean $\times 1.96 \times \sqrt{2}$, confirmed a plateau had been achieved. HR was
193 measured continuously throughout both trials (Polar RS400, Polar Electro Oy, Kempele, Finland) with
194 an average of the final 2 min of each stage used in analysis. A rating of perceived exertion (6-20 scale)
195 was also taken during the final 30 s of each 5 min stage as a subjective indicator of effort. Time to
196 volitional exhaustion was recorded to the nearest second for the continuous run at $s\dot{V}O_{2max}$, and blood
197 lactate was taken immediately after.

198
199 $\dot{V}O_2$ is typically expressed as a ratio to body mass, however this approach is only valid when the
200 relationship between these two variables is in direct proportion, which is often not the case in humans²³.
201 Thus, it is recommended that specific scaling exponents are calculated for different populations of
202 participants²³. An allometric scaling exponent was therefore obtained by combining baseline data from
203 participants in the present study with a larger cohort of homogenous male runners ($n=35$, 17.3 ± 1.4
204 years, 62.8 ± 6.5 kg, 1.77 ± 0.06 m, 70.4 ± 7.0 ml.kg⁻¹.min⁻¹). Natural logarithms (ln) of absolute $\dot{V}O_2$
205 and body mass were taken for sLTP -1 km.h⁻¹ and linear regression was used to obtain values for the
206 model $ln_y = ln_a + b.ln_x$, where [a] is the scaling constant and [b] is the scaling exponent corresponding
207 to body mass. The allometric model was identified as $= 104.6 x^{0.85}$, therefore a scaling exponent of
208 0.85 (95% confidence interval (CI) = 0.53-1.17) was used in subsequent analysis of RE, expressed as
209 kJ.kg^{-0.85}.km⁻¹.

210

211 Data used for scaling was analysed using SPSS Statistics (v22, IBM, New York USA). Normality of
212 distribution was confirmed visually using Q-Q plots and objectively with a Shapiro-Wilks statistic.
213 Prior to scaling, the assumption of homoscedasticity was assessed using a scatterplot of the standardized
214 residual and standardized predicted variables. Data collected in trials were analysed using Microsoft
215 Excel 2013 and a published spreadsheet²⁴. Values are presented as mean \pm SD, unless otherwise stated.
216 ES's for the measures taken during submaximal running were calculated as the difference between
217 change scores divided by the standard deviation of pre-test scores across both trials. For measures taken
218 during the run to exhaustion, ES's are presented as a ratio between the mean difference between trials
219 and the within-subject standard deviation. ES values were interpreted as trivial (<0.2), small (0.2-0.59),
220 moderate (0.6-1.2) and large (>1.2)²⁵. Magnitude based inferences were calculated using MDC₉₅ values
221 from previous reliability work in this population¹⁹.

222

223 As PAPE response appears to be related to strength status⁴, a partial correlation that controlled for the
224 influence of pre-test score was performed in SPSS Statistics on the percentage change score for RE in
225 the DJ trial and CMJ performance. Quantification of individual responses to an intervention requires
226 consideration of the error associated with measurement, which can be derived from the control
227 condition of an experiment²⁶. Thus, inter-individual responses were explored by calculating the true
228 individual difference using the formula²⁶:

$$229 \sqrt{SD_{DJ}^2 - SD_C^2}$$

230 Where SD_{DJ} and SD_C represents the SD of the change score for RE or the SD of scores for TTE in the
231 DJ and C trials respectively. This value was also expressed in standardized units (with 95% confidence
232 limits), by dividing the true individual difference by the pooled pre-intervention standard deviation²⁶.
233 Expressing individual responses in standardized units (an effect size) allows practitioners to interpret
234 more easily the effectiveness of the intervention on individual athletes.

235

236

237 **Results**

238

239 The difference between the 5 min warm-ups that preceded both trials was negligible ($\dot{V}O_{2\max}$: $61.2 \pm$
240 4.4% vs $60.0 \pm 4.2\%$, ES=0.17). Table 2 displays the results for measures taken during submaximal
241 running before and after the DJ and C interventions. Participants perceived readiness to perform was
242 moderately higher (ES: 0.62) following DJ compared to the C condition. Performing DJ provided a
243 possible benefit (-3.7% , ES: 0.67) to RE. The effect on blood lactate, HR and RPE was trivial (ES:
244 <0.2). The effect of DJ on TTE at $s\dot{V}O_{2\max}$ and blood lactate response was most likely trivial (ES: <0.2)
245 compared to the C trial (Table 2).

246

247 ***Table 2 about here***

248

249 A moderate negative correlation ($r=-0.55$ (95% CI: -0.25 to -0.90), $p=0.028$) was observed between the
250 change in RE following DJ and CMJ height after controlling for pre-intervention RE. The true
251 individual difference for change in RE in the DJ trial was calculated as $0.19 \text{ kJ}\cdot\text{kg}^{-0.85}\cdot\text{km}^{-1}$ (95% CI:
252 0.15 - $0.23 \text{ kJ}\cdot\text{kg}^{-0.85}\cdot\text{km}^{-1}$). In standardized units, the individual responses were 0.42 (95% CI: 0.33 - 0.51)
253 representing a small individual effect to the DJ intervention for RE. These individual changes in RE for
254 the DJ trial are shown with the mean group change in Figure 1. Individual responses in TTE were
255 trivial (6.5 s , ES: 0.04).

256

257

258 ***Figure 1 about here***

259

260

261 **Discussion**

262

263 The aim of this experiment was to examine whether the inclusion of DJ in the warm-up routine of a
264 group of high-performing junior middle-distance runners could acutely influence RE, and TTE at
265 $s\dot{V}O_{2\max}$. Findings suggest that DJ provide a moderate benefit (-3.7% , ES: 0.67) to RE but TTE was

266 unaffected. In the context of MDC_{95} values, DJ were considered a possibly beneficial stimulus to
267 enhance RE. There were small differences in individual RE responses to DJ, and this appears partly
268 attributable to an individual's explosive strength capabilities.

269

270 Despite a large body of evidence demonstrating positive acute effects from high-load resistance⁴ and
271 ballistic³ exercise on explosive power tasks, very few studies have been conducted examining whether
272 endurance-related parameters could also benefit. This is the first study to show improvements (-3.7%,
273 ES: 0.67) in RE following a single-set (6-repetitions) of high-intensity plyometric exercise. This effect
274 is similar in magnitude to improvements observed in RE following chronic periods (6-14 weeks) of
275 strength training in distance runners¹². Using a similar protocol to the current study, Barnes and
276 colleagues¹³ observed large (-6.0%, ES: 1.40) improvements in RE following 6x10 s sprints with a
277 weighted vest (20% body mass). It is likely that the larger improvements noted in the Barnes¹³ study
278 compared to the present study were a result of the higher volume of loaded conditioning work
279 performed. Similarly, Feros and co-workers¹⁴ found that using isometric contractions (5x5 s) on a
280 rowing ergometer increased mean power for the first half of a 1 km rowing time trial by 6.6% (ES:
281 0.64). Collectively, these data suggest a moderate-large benefit for task-specific conditioning activities
282 to enhance performance-related outcomes.

283

284 There were trivial differences in blood lactate and HR during sub-maximal running between trials (ES:
285 <0.2). The absence of change in blood lactate value suggests that the contribution from anaerobic
286 glycolysis to energy expenditure did not alter, thus total metabolic cost of running was also reduced.
287 The lack of change in HR during the DJ trial is a somewhat surprising result, as a reduction in energy
288 cost would imply that a lower volume of oxygen is required by the active muscles, It may be possible
289 that noticeable reductions in HR only occur when changes in RE are large. This is supported by findings
290 from Barnes et al¹³ who observed large (ES: 1.40) improvements in RE and small (ES: 0.45) reductions
291 in submaximal HR. This indicates that cardiorespiratory-related mechanisms are unlikely to be
292 responsible for the change observed in RE. One or more acute alterations in neuromuscular
293 characteristics, which are also known to underpin RE, are therefore the likely mechanism of effect.

294

295 The mechanistic bases for the acute improvements in performance-related outcomes observed following
296 a high-intensity conditioning activity remains controversial⁵. It is recognized that enhancement of
297 voluntary muscle contraction via increases in MLC phosphorylation lasts 4-6 min⁷, thus it seems
298 unlikely that this mechanism was responsible for the improvement observed. A high-intensity
299 plyometric exercise, which involves augmented eccentric muscle contractions, may also activate a large
300 pool of motor units, which are then accessible during subsequent exercise⁶. Thus, for any given sub-
301 maximal exercise performed shortly after, a lower relative intensity of activation is required, thereby
302 reducing energy cost²⁷. It may also be possible that plyometric exercise, which elicits a stretch reflex
303 response, acutely elevates the transmittance of excitation potentials via the Ia afferent, which increases
304 output from the motoneuron pool⁶, observable on an electromyography trace as an increase in the H-
305 wave. Indeed, an increase in H-wave amplitude has been observed for 5-11 min in the knee extensors
306 following maximal voluntary contraction⁹. Acute changes in leg stiffness have previously been shown
307 during endurance running¹³ in response to a PAPE stimulus. It is therefore possible that an increase in
308 musculotendinous stiffness may also have helped optimize the length-tension relationship of muscles,
309 thereby reducing the magnitude and velocity of shortening, and therefore lowering energy usage²⁷.
310 Indeed, higher Achilles tendon stiffness is associated with superior RE²⁸, implying that an acute
311 improvement in this quality may reduce the energy cost of running. Elevations in hormones such as
312 testosterone¹⁰ and plasma catecholamines⁵, have also been reported immediately following a loaded
313 conditioning activity, and are associated with improved physical performance. Finally, we cannot
314 discount the possibility that the DJ provided a greater rise in muscle temperature compared to the C
315 trial⁸. Given the low volume (six repetitions) of DJ used and the absence of change in metabolic and
316 cardiovascular parameters this mechanism seems unlikely.

317

318 Although it is clear that endurance-trained athletes are capable of benefitting from a PAPE protocol¹¹,
319 the phenomenon is more likely to occur in stronger individuals⁴. This is partly confirmed by findings
320 in the present study as explosive strength capability, measured via a CMJ, was correlated ($r=-0.55$,
321 $p=0.028$) with change in RE following DJ. This suggests that distance runners with greater levels of

322 explosive strength are more likely to benefit from a PAPE protocol. In this study, DJ were performed
323 from a height equal to a participants CMJ, therefore more explosive individuals received a higher
324 stimulus than those who were less explosive. The possibility that differences in the absolute intensity
325 of the stimulus applied explain the improvement observed in change in RE following DJ cannot be
326 discounted. There are alternative options for determining an appropriate box height for performing DJ,
327 which could be explored in the future. A box height that maximizes an individual's reactive strength
328 index (the ratio between jump height in metres and contact time) has been proposed as a method of
329 selecting DJ intensity²⁹. This method has been shown to produce a DJ height approximately 10 cm
330 lower than CMJ height in physically active males³⁰, thus it is unlikely a greater PAPE would have been
331 observed using this strategy.

332

333 Identification of individual responses is only possible if the random within-subject variation is
334 accounted for by calculating the extent to which the net mean effect of an intervention differs between
335 participants. The true individual responses to DJ were small, even when uncertainty was accounted for
336 (ES: 0.42, 95% CI: 0.33-0.51, Figure 1). The overall effect of DJ, after removing the effects of random
337 variation can therefore be summarized as $-0.35 \pm 0.19 \text{ kJ kg}^{-0.85} \text{ km}^{-1}$ (mean \pm SD of individual response)
338 or, in standardized units 0.67 ± 0.42 . Thus, the positive effect typically ranged from small (ES: 0.25) to
339 borderline moderate-large (ES: 1.09).

340

341 TTE at $\dot{V}O_{2\max}$ and end blood lactate were very similar between trials (ES: <0.2). Following a PAPE-
342 inducing stimulus, a state of neuromuscular activation and fatigue coexist⁶, therefore selecting a
343 recovery time that allows fatigue to dissipate, yet a state of activation to remain, is essential to ensure a
344 benefit is realized. In the present study, RE was measured 10 min after completion of DJ. The run to
345 exhaustion then started 16-min after the DJ, thus any PAPE may have dissipated by this point in the
346 trial. A similar response pattern was observed in a 20 km cycle time trial after heavy (5-repetition
347 maximum) leg pressing exercise and a 10 min recovery¹⁵. Overall time was significantly quicker
348 following heavy leg pressing, however this improvement was largely the consequence of a higher power
349 output in the first 2 km of the time trial, with little difference observed in the remainder of the trial

350 compared to a control condition¹⁵. As TTE at $s\dot{V}O_{2max}$ is influenced by different physiological factors
351 compared to RE², it is also possible that this parameter does not benefit from a warm-up protocol of
352 this nature. Predicted $s\dot{V}O_{2max}$ has shown improvements following a warm-up that included weighted
353 vest sprints and a similar recovery (~20 min) to the present study. Thus, future research should
354 investigate the efficacy of various loaded conditioning activities on key performance-related measures.

355

356 It is important to highlight that the pre-intervention values for RE displayed a difference of 4.8%
357 between trials (see Table 2), which is greater than the within-subject variation previously recorded in a
358 similar cohort¹⁹. Given the design of the study, blinding of participants to the intervention they were
359 about to perform, careful calibration of equipment, and high similarity between inter-trial warm-up
360 intensities, it is not obvious why this difference occurred. A difference of 2.9% was present in the pre-
361 intervention $\dot{V}O_2$ values, which is similar to intra-individual variability previously recorded (2.8%)¹⁹.
362 When combined with subtle differences in body mass (0.3%) and respiratory exchange ratio values
363 (0.7%), both in favor of the DJ trial, this appears to have generated inflated pre-intervention values in
364 the DJ trial.

365

366 **Conclusions**

367

368 Including six DJ, 10-min prior to a run just below lactate turn-point provides a moderate benefit to RE
369 in high-performing junior male middle-distance runners. Runners who display higher levels of
370 explosive strength seem more likely to experience a positive response. It appears less likely that
371 continuous efforts at $s\dot{V}O_{2max}$ are likely to benefit, however this may have been influenced by the timing
372 of the protocol in this study.

373

374 **Practical applications**

375

- 376 • Incorporating a simple high-intensity plyometric-based exercise in the warm-up routine of a
377 distance runner possibly provides a means of acutely improving RE.

- 378
- Middle-distance runners should experiment with incorporating a set of DJ into their warm-up
- 379 routine 10 min prior to a continuous run at approximately sLTP.
- 380
- A moderate improvement in RE should allow a higher absolute speed to be attained for the
- 381 same relative submaximal intensity, thus augmenting the training response, however further
- 382 research is required to verify this suggestion.
- 383

Accepted

384 **References**

385

- 386 1. Jones AM, Koppo K, Burnley M. Effects of prior exercise on metabolic and gas exchange
387 responses to exercise. *Sports Med* 2003;33(13):949-971.
- 388 2. Thompson M. Physiological and biomechanical mechanisms of distance specific human
389 running performance. *Integr Comp Biol* 2017;57(2):293-300.
- 390 3. Maloney SJ, Turner AN, Fletcher IM. Ballistic exercise as a pre-activation stimulus: a review
391 of the literature and practical applications. *Sports Med* 2014;44(10):1347-1359.
- 392 4. Seitz LB, Haff GG. Factors modulating post-activation potentiation of jump, sprint, throw,
393 and upper-body ballistic performances: a systematic review with meta-analysis. *Sports Med*
394 2016;46(2):231-240.
- 395 5. Cuenca-Fernández F, Smith IC, Jordan MJ, et al. Nonlocalized postactivation performance
396 enhancement (PAPE) effects in trained athletes: a pilot study. *Appl Physiol Nutr Metab*
397 2017;42(10):1122-1125.
- 398 6. Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on
399 performance of subsequent explosive activities. *Sports Med* 2009;39(2):147-166.
- 400 7. Macintosh B, Willis E. Should postactivation potentiation be the goal of your warm-up? *Appl*
401 *Physiol Nutr Metab* 2012;88(6):2088-2096.
- 402 8. Sargeant AJ. Effect of muscle temperature on leg extension force and short-term power
403 output in humans. *Eur J Appl Physiol Occ Physiol* 1987;56(6):693-698.
- 404 9. Folland JP, Wakamatsu T, Fimland MS. The influence of maximal isometric activity on
405 twitch and H-reflex potentiation, and quadriceps femoris performance. *Eur J Appl Physiol*
406 2008;104(4):739-748.
- 407 10. Crewther BT, Cook C, Cardinale M, et al. Two emerging concepts for elite athletes. *Sports*
408 *Med* 2011;41(2):103-123.
- 409 11. Blagrove RC, Howatson G, Hayes PR. Use of loaded conditioning activities to potentiate
410 middle- and long-distance performance: a narrative review and practical applications. *J*
411 *Strength Cond Res* 2018 doi: 10.1519/JSC.0000000000002456.
- 412 12. Blagrove RC, Howatson G, Hayes PR. Effects of strength training on the physiological
413 determinants of middle-and long-distance running performance: a systematic review. *Sports*
414 *Med* 2018;48(5):1117-1149.
- 415 13. Barnes KR, Hopkins WG, McGuigan MR, et al. Warm-up with a weighted vest improves
416 running performance via leg stiffness and running economy. *J Sci Med Sport* 2015;18(1):103-
417 108.
- 418 14. Feros SA, Young WB, Rice AJ, et al. The effect of including a series of isometric
419 conditioning contractions to the rowing warm-up on 1,000-m rowing ergometer time trial
420 performance. *J Strength Cond Res* 2012;26(12):3326-3334.
- 421 15. Silva RA, Silva-Júnior FL, Pinheiro FA, Souza PF, Boulosa DA, Pires FO. Acute prior heavy
422 strength exercise bouts improve the 20-km cycling time trial performance. *J Strength Cond*
423 *Res* 2014;28(9):2513-2520.
- 424 16. Bomfim Lima J, Marin D, Barquilha G, et al. Acute effects of drop jump potentiation
425 protocol on sprint and countermovement vertical jump performance. *Hum Mov Sci*
426 2011;12(4):324-330.
- 427 17. Moore SA, McKay HA, Macdonald H, et al. Enhancing a somatic maturity prediction model.
428 *Med Sci Sports Exerc* 2015;47(8):1755-1764.
- 429 18. Jones AM. Middle- and Long Distance Running. In: Winter EM JA, Davison RC, Bromley
430 PD, Mercer TH, ed. *BASES Sport and Exercise Physiology Testing Guidelines: Vol. 1 – Sport*
431 *Testing*. Taylor & Francis e-Library; 2009:147-155.
- 432 19. Blagrove RC, Howatson G, Hayes PR. Test-retest reliability of physiological parameters in
433 elite junior distance runners following allometric scaling. *Eur J Sport Sci* 2017;17(10):1231-
434 1240.
- 435 20. Hayes PR, Walker A. Pre-exercise stretching does not impact upon running economy. *J*
436 *Strength Cond Res* 2007;21(4):1227.

- 437 21. Ingham SA, Fudge BW, Pringle JS, et al. Improvement of 800-m running performance with
438 prior high-intensity exercise. *Int J Sports Physiol Perf* 2013;8(1):77-83.
- 439 22. Peronnet F, Massicotte D. Table of nonprotein respiratory quotient: an update. *Can J Sport*
440 *Sci* 1991;16(1):23-29.
- 441 23. Packard GC, Boardman TJ. The use of percentages and size-specific indices to normalize
442 physiological data for variation in body size: wasted time, wasted effort? *Comp Biochem*
443 *Physiol A Mol Integr Physiol* 1999;122(1):37-44.
- 444 24. Batterham AM. A spreadsheet for analysis of straightforward controlled trials. *Sportsci*
445 2003;7.
- 446 25. Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports*
447 *Physiol Perf* 2006;1(1):50-57.
- 448 26. Atkinson G, Batterham AM. True and false interindividual differences in the physiological
449 response to an intervention. *Exp Physiol* 2015;100(6):577-588.
- 450 27. Fletcher JR, MacIntosh BR. Running economy from a muscle energetics perspective. *Front*
451 *Physiol* 2017;8:433.
- 452 28. Arampatzis A, De Monte G, Karamanidis K, et al. Influence of the muscle-tendon unit's
453 mechanical and morphological properties on running economy. *J Exp Biol.*
454 2006;209(17):3345-3357.
- 455 29. Flanagan EP, Comyns TM. The use of contact time and the reactive strength index to
456 optimize fast stretch-shortening cycle training. *Strength Cond J* 2008;30(5):32-38.
- 457 30. Byrne PJ, Moran K, Rankin P, et al. A comparison of methods used to identify 'optimal' drop
458 height for early phase adaptations in depth jump training. *J Strength Cond Res*
459 2010;24(8):2050-2055.

461

462

Characteristic	Mean \pm SD
Age (years)	17.6 \pm 1.2
Body mass (kg)	63.4 \pm 6.3
Stature (m)	1.76 \pm 0.06
$\dot{V}O_{2\max.}$ (mL·kg ⁻¹ ·min ⁻¹)	70.7 \pm 5.2
sLTP (km·h ⁻¹)	16.7 \pm 1.4
s $\dot{V}O_{2\max.}$ (km·h ⁻¹)	21.7 \pm 1.4
CMJ (m)	0.416 \pm 0.065

463

464 **Table 1.** Characteristics of study participants ($n=17$). $\dot{V}O_{2\max.}$ = maximal oxygen uptake,

465 sLTP = speed at lactate turn point, s $\dot{V}O_{2\max.}$ = speed associated with maximal oxygen uptake,

466 CMJ = counter-movement jump.

467

468

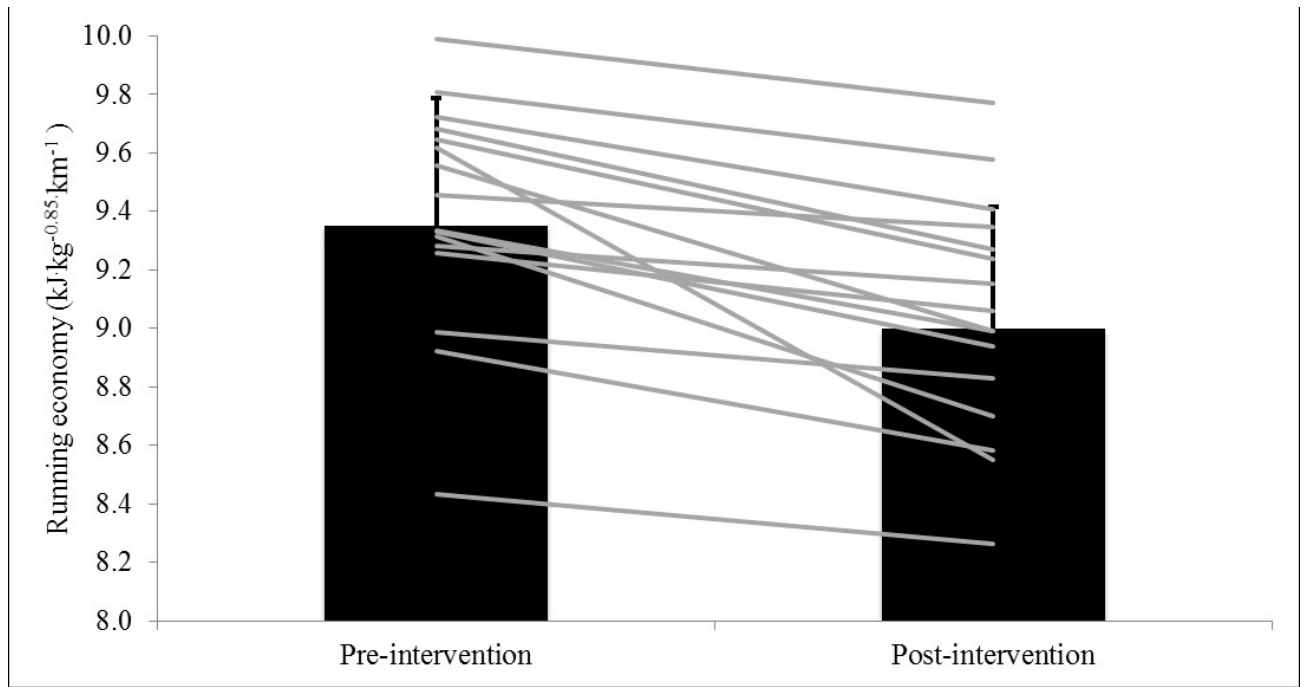
Variable	Trial	Pre-intervention	Post-intervention	Mean percentage change \pm 95% CI	Effect size (interpretation)	Magnitude based inference
Perceived readiness (1-10)	DJ	-	6.9 \pm 0.9	13.3 \pm 9.8	0.62 (moderate)	Possibly beneficial
	C	-	6.1 \pm 1.3			
<i>Submaximal running</i>						
Running economy (kJ·kg ^{-0.85} ·km ⁻¹)	DJ	9.35 \pm 0.44	9.00 \pm 0.42	-3.7 \pm 1.3	0.67 (moderate)	Possibly beneficial
	C	8.92 \pm 0.41	8.88 \pm 0.41	-1.0 \pm 0.8		
Blood lactate (mMol·L ⁻¹)	DJ	2.8 \pm 0.9	2.4 \pm 0.8	-14.3 \pm 6.1	0.15 (trivial)	Very likely trivial
	C	2.6 \pm 0.8	2.3 \pm 0.8	-11.5 \pm 6.2		
Heart rate (b·min ⁻¹)	DJ	172 \pm 10	173 \pm 10	0.6 \pm 0.4	0.08 (trivial)	Most likely trivial
	C	171 \pm 11	173 \pm 10	1.1 \pm 0.6		
RPE	DJ	12 \pm 1	13 \pm 1	6.8 \pm 6.2	0.12 (trivial)	Most likely trivial
	C	12 \pm 2	13 \pm 1	5.4 \pm 3.6		
<i>Run to exhaustion</i>						
Time to exhaustion (s)	DJ	-	160 \pm 39	1.3 \pm 6.5	0.06 (trivial)	Most likely trivial
	C	-	158 \pm 34			
End lactate (mMol·L ⁻¹)	DJ	-	8.1 \pm 2.1	2.5 \pm 7.7	0.13 (trivial)	Most likely trivial
	C	-	7.9 \pm 1.9			

469

470 **Table 2.** Results and qualitative inferences of measures taken during submaximal running at 20% Δ below $\dot{V}O_2$ at lactate turn-point and for the

471 run to exhaustion at speed associated with $\dot{V}O_{2max}$. CI = confidence interval, DJ = depth jumps, C = control trial (body weight quarter squats),

472 RPE = rating of perceived exertion (6-20 scale)



473

474

475 **Figure 1.** Mean±SD change and individual values ($n=17$) for running economy at 20% Δ below $\dot{V}O_2$

476 associated with lactate turn-point in the depth jump trial

477