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

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Abstract

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

Design: Randomized crossover study.

Methods: Seventeen national- and international-standard male distance runners (17.6 ± 1.2 years, 63.4 ± 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 60% $\dot{V}O_{2max}$, participants performed a 5 min run at 20%Δ below oxygen uptake corresponding with lactate turn-point to determine pre-intervention RE. Participants then completed either six DJ from a box equivalent to their best counter-movement jump (CMJ) or a control condition (C) involving body weight quarter squats. After a 10 min passive recovery, another 5 min sub-maximal run was performed followed by a run to exhaustion at s$\dot{V}O_{2max}$.

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

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

Keywords: warm-up, potentiation, pre-activation, running, physiology, plyometrics

Abbreviations

C = control condition

CI = confidence interval

CMJ = counter-movement jump

DJ = depth jumps

HR = heart rate

LTP = lactate turnpoint

MDC_{95} = minimal detectable change (95% confidence)

MLC = myosin light chains

PAPE = post-activation performance enhancement

RE = running economy

sLTP = speed associated with lactate turnpoint

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

TE = typical error

TTE = time to exhaustion

Introduction

Warm-up strategies for endurance athletes typically aim to achieve acute metabolic and cardiovascular adjustments, which enhance the oxygen uptake ($\dot{V}O_2$) kinetic response[1]. Distance running performance is underpinned by several important physiological determinants, which are limited by metabolic and cardiovascular factors, however neuromuscular characteristics also play an important role[2]. It is currently unknown whether high-intensity strength-based activities incorporated into a warm-up are capable of acutely activating the neuromuscular system, thus providing additional benefits to the determinants of performance in distance runners.

For short-duration athletic tasks, such as sprints and jumps, there is a large body of evidence demonstrating possible improvements in performance 5-12 min after completion of a ballistic exercise (e.g. plyometrics) or a heavy resistance exercise (>85% one repetition maximum)[3,4]. This enhancement of voluntary movement has been referred to as 'post-activation performance enhancement' (PAPE)[5], and can be explained by a number of physiological mechanisms. Most notably, acute enhancement in voluntary movement have often been attributed to a 'potentiation' response, which increases myosin light chains (MLC) phosphorylation, thereby enhancing rate of force development[6]. However, this effect is short-lived (~5 min)[7] and has rarely been observed during voluntary contractions. Other unrelated physiological effects that may explain a PAPE include: an increase in muscle temperature[8], modulation of the H-reflex[9], an increase in motor unit recruitment[6], elevations in hormones[10], and changes in limb stiffness[3]. Although, some of these mechanisms have been shown to facilitate a short-term improvement in explosive power performance, there has been recent speculation that endurance-related outcomes may also benefit[11].

Improvements in RE and time-trial performance have been reported following a chronic strength training intervention[12], however only a few studies have reported how these methods might acutely enhance these parameters[13-15]. A series of sprints (6x10 s) wearing a weighted vest prior to an incremental treadmill run has been shown to improve peak running speed and RE via changes in leg stiffness, compared to a warm-up which included non-weighted sprints[13]. High-load resistance exercise has also been shown to enhance 20 km time-trial performance in well-trained cyclists[15]. A similar finding was observed in a group of elite rowers during a 1 km time trial, with power in the first 500 m displaying improvement following a series of 5x5 s isometric contractions on the rowing ergometer[14]. Both of these investigations[14,15] attributed the improvements to a potentiation response. A PAPE is transient, therefore selecting an appropriate recovery duration following a strength-based stimulus is crucial to ensuring fatigue has dissipated sufficiently yet a post-activation state remains. A rest period of 5-10 min following a set of voluntary contractions has been suggested for endurance athletes[11], and the aforementioned studies in endurance runners[13] and cyclists[15] utilized a 10 min recovery.

Simple strategies incorporated into warm-up routines, which have the potential to improve performance, are likely to be of considerable interest to athletes and their coaches. Chronic plyometric training has been shown to enhance RE and performance[12] and plyometrics have been used to acutely enhance sprint performance in athletically trained males[16]. Importantly, plyometrics do not require specialist or cumbersome equipment and can be easily utilized in a field-based setting with athletes. Based on the aforementioned information, we conjecture that a simple plyometric exercise would improve RE and performance. Consequently, the aim of this study was to examine the influence of performing depth jumps (DJ) on RE and TTE in a group of high-performing junior middle-distance runners.

Methods

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

Table 1 about here

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

The first testing session involved a discontinuous submaximal incremental running assessment followed by a $\dot{V}O_{2max}$ test with the treadmill gradient inclined to 1% throughout. Following a 5 min warm-up, participants completed 5-7 bouts of running each lasting 3 min with 30 s passive rest to allow for a capillary blood sample to be taken. The speed of the first stage was selected based upon the participants best times and published recommendations[18]. Speed was subsequently increased by 1 $km \cdot h^{-1}$ each stage until lactate turn-point (LTP), defined as a rise in lactate of >1 $mMol \cdot L^{-1}$ from the previous stage[19], was reached. Following a 5 min passive recovery, participants ran at the speed associated with their LTP (sLTP) and every minute thereafter, the treadmill speed increased by 1 $km \cdot h^{-1}$ until volitional exhaustion. $\dot{V}O_{2max.}$ was defined as the highest 30 s mean $\dot{V}O_2$ value obtained during the $\dot{V}O_{2max.}$ test. $s\dot{V}O_{2max}$ was identified as the final speed achieved for >30 s during the assessment of $\dot{V}O_{2max}$. After 20 min active recovery (slow walking), participants performed three maximum CMJs with hands placed on hips on a force plate (Kistler 9287BA, Kistler Instruments Ltd, Hampshire, UK) sampling at 1000 Hz, with 90 s rest permitted between each attempt. Jump height was determined by calculating centre of mass displacement from the participants take-off velocity. CMJ height was used to individualize box height (to the nearest 0.01 m) for the DJ. Participants were then familiarized with the exercises to be used in the two warm-up scenarios (DJ and C).

On the second and third visits to the laboratory, participants completed two performance trials in a quasi-randomized counter-balanced order (ABBA method). One trial included a warm-up involving a set of DJ and the other a control condition (C), involving unloaded quarter squats. The two trials commenced with a warm-up at 60% $\dot{V}O_{2max}$ followed by 5 min of running at a speed corresponding to 20%Δ below $\dot{V}O_2$ at LTP[20]. The delta value represents the difference between $\dot{V}O_2$ at sLTP and $\dot{V}O_{2max}$. Speed was determined by deducting 20% of this delta value from $\dot{V}O_2$ at LTP and entering this value into the linear regression equation for the speed-$\dot{V}O_2$ relationship for each participant. Following a 5 min passive recovery, participants completed six repetitions of either DJ or the C exercise. For the DJ, participants placed their feet on the edge of the box, were instructed to step off a box whilst maintaining an extended knee on the supporting leg, and rebound as high as possible whilst minimizing their ground contact time. In the C trial, participants were instructed to descend into a shallow squat position (~140^{o} knee flexion) with heels remaining in contact with the ground, before slowly returning to standing. This exercise was included to mask the active effect that was anticipated from the DJ and minimize the likelihood of a placebo response. Both protocols were followed by a further 10 min of passive rest to allow neuromuscular fatigue to dissipate but maximize the likelihood of a PAPE response being realized. Immediately prior to remounting the treadmill, participants were asked to provide a rating (1-10) of perceived readiness[21]. To evaluate the effect of the intervention on RE, participants then ran for 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 at s$\dot{V}O_{2max}$. Participants were blinded to the duration they had been running for throughout the trial.

At the start of each testing session, participant’s body mass was taken using digital scales (MPMS-230, Marsden Weighing Group, Oxfordshire, UK) to the nearest 0.1 kg. Stature and sitting height were also measured with a stadiometer (SECA GmbH & Co., Hamburg, Germany) to the nearest 0.01 m for prediction of maturity offset. A 20 µL blood sample was taken from the earlobe at rest and the end of every running stage across all testing sessions. Samples were hemolysed and subsequently analyzed for blood lactate concentration (Biosen C-Line, EKF Diagnostic, Barleben, Germany). Gas exchange was measured breath-by-breath via an automated open circuit metabolic cart (Oxycon Pro, Enrich Jaeger GmbH, Hoechberg, Germany) calibrated to manufacturer’s recommendations. Typical error (TE) of measurement has previously been reported for RE using this system in junior distance runners (<2%) and test-retest reliability is considered excellent (intra-class correlation coefficient: >0.9)[19]. Following filtering of breath-by-breath data to remove errant breathes, oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were averaged for the final 2 min of both 5 min stages in the main trials and were subsequently used to calculate RE in terms of energy cost using updated non-protein respiratory quotients[22]. To verify a steady-state had been achieved, the difference between the first 60 s of the final two minutes and the last 60 s was calculated. A difference smaller than the minimal detectable change (MDC_{95}), calculated as TE of the mean x 1.96 x $\sqrt{2}$, confirmed a plateau had been achieved. HR was measured continuously throughout both trials (Polar RS400, Polar Electro Oy, Kempele, Finland) with an average of the final 2 min of each stage used in analysis. A rating of perceived exertion (6-20 scale) was also taken during the final 30 s of each 5 min stage as a subjective indicator of effort. Time to volitional exhaustion was recorded to the nearest second for the continuous run at $s\dot{V}O_{2max}$, and blood lactate was taken immediately after.

$\dot{V}O_2$ is typically expressed as a ratio to body mass, however this approach is only valid when the relationship between these two variables is in direct proportion, which is often not the case in humans[23]. Thus, it is recommended that specific scaling exponents are calculated for different populations of participants[23]. An allometric scaling exponent was therefore obtained by combining baseline data from participants in the present study with a larger cohort of homogenous male runners (*n*=35, 17.3 ± 1.4 years, 62.8 ± 6.5 kg, 1.77 ± 0.06 m, 70.4 ± 7.0 $ml.kg^{-1}.min^{-1}$). Natural logarithms (*In*) of absolute $\dot{V}O_2$ and body mass were taken for sLTP -1 $km{\cdot}h^{-1}$ and linear regression was used to obtain values for the model $ln_y = ln_a + b.ln_x$, where [a] is the scaling constant and [b] is the scaling exponent corresponding to body mass. The allometric model was identified as $= 104.6\ x^{0.85}$, therefore a scaling exponent of 0.85 (95% confidence interval (CI) = 0.53-1.17) was used in subsequent analysis of RE, expressed as $kJ{\cdot}kg^{-0.85}{\cdot}km^{-1}$.

Data used for scaling was analysed using SPSS Statistics (v22, IBM, New York USA). Normality of distribution was confirmed visually using Q-Q plots and objectively with a Shapiro-Wilks statistic. Prior to scaling, the assumption of homoscedasticity was assessed using a scatterplot of the standardized residual and standardized predicted variables. Data collected in trials were analysed using Microsoft Excel 2013 and a published spreadsheet[24]. Values are presented as mean ± SD, unless otherwise stated. ES's for the measures taken during submaximal running were calculated as the difference between change scores divided by the standard deviation of pre-test scores across both trials. For measures taken during the run to exhaustion, ES's are presented as a ratio between the mean difference between trials and the within-subject standard deviation. ES values were interpreted as trivial (<0.2), small (0.2-0.59), moderate (0.6-1.2) and large (>1.2)[25]. Magnitude based inferences were calculated using MDC_{95} values from previous reliability work in this population[19].

As PAPE response appears to be related to strength status[4], a partial correlation that controlled for the influence of pre-test score was performed in SPSS Statistics on the percentage change score for RE in the DJ trial and CMJ performance. Quantification of individual responses to an intervention requires consideration of the error associated with measurement, which can be derived from the control condition of an experiment[26]. Thus, inter-individual responses were explored by calculating the true individual difference using the formula[26]:

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

Where SD_{DJ} and SD_C represents the SD of the change score for RE or the SD of scores for TTE in the DJ and C trials respectively. This value was also expressed in standardized units (with 95% confidence limits), by dividing the true individual difference by the pooled pre-intervention standard deviation[26]. Expressing individual responses in standardized units (an effect size) allows practitioners to interpret more easily the effectiveness of the intervention on individual athletes.

Results

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

Table 2 about here

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

Figure 1 about here

Discussion

The aim of this experiment was to examine whether the inclusion of DJ in the warm-up routine of a group of high-performing junior middle-distance runners could acutely influence RE, and TTE at s$\dot{V}O_{2max}$. Findings suggest that DJ provide a moderate benefit (-3.7%, ES: 0.67) to RE but TTE was unaffected. In the context of MDC_{95} values, DJ were considered a possibly beneficial stimulus to enhance RE. There were small differences in individual RE responses to DJ, and this appears partly attributable to an individual's explosive strength capabilities.

Despite a large body of evidence demonstrating positive acute effects from high-load resistance[4] and ballistic[3] exercise on explosive power tasks, very few studies have been conducted examining whether endurance-related parameters could also benefit. This is the first study to show improvements (-3.7%, ES: 0.67) in RE following a single-set (6-repetitions) of high-intensity plyometric exercise. This effect is similar in magnitude to improvements observed in RE following chronic periods (6-14 weeks) of strength training in distance runners[12]. Using a similar protocol to the current study, Barnes and colleagues[13] observed large (-6.0%, ES: 1.40) improvements in RE following 6x10 s sprints with a weighted vest (20% body mass). It is likely that the larger improvements noted in the Barnes[13] study compared to the present study were a result of the higher volume of loaded conditioning work performed. Similarly, Feros and co-workers[14] found that using isometric contractions (5x5 s) on a rowing ergometer increased mean power for the first half of a 1 km rowing time trial by 6.6% (ES: 0.64). Collectively, these data suggest a moderate-large benefit for task-specific conditioning activities to enhance performance-related outcomes.

There were trivial differences in blood lactate and HR during sub-maximal running between trials (ES: <0.2). The absence of change in blood lactate value suggests that the contribution from anaerobic glycolysis to energy expenditure did not alter, thus total metabolic cost of running was also reduced. The lack of change in HR during the DJ trial is a somewhat surprising result, as a reduction in energy cost would imply that a lower volume of oxygen is required by the active muscles, It may be possible that noticeable reductions in HR only occur when changes in RE are large. This is supported by findings from Barnes et al[13] who observed large (ES: 1.40) improvements in RE and small (ES: 0.45) reductions in submaximal HR. This indicates that cardiorespiratory-related mechanisms are unlikely to be responsible for the change observed in RE. One or more acute alterations in neuromuscular characteristics, which are also known to underpin RE, are therefore the likely mechanism of effect.

The mechanistic bases for the acute improvements in performance-related outcomes observed following a high-intensity conditioning activity remains controversial[5]. It is recognized that enhancement of voluntary muscle contraction via increases in MLC phosphorylation lasts 4-6 min[7], thus it seems unlikely that this mechanism was responsible for the improvement observed. A high-intensity plyometric exercise, which involves augmented eccentric muscle contractions, may also activate a large pool of motor units, which are then accessible during subsequent exercise[6]. Thus, for any given sub-maximal exercise performed shortly after, a lower relative intensity of activation is required, thereby reducing energy cost[27]. It may also be possible that plyometric exercise, which elicits a stretch reflex response, acutely elevates the transmittance of excitation potentials via the Ia afferent, which increases output from the motoneuron pool[6], observable on an electromyography trace as an increase in the H-wave. Indeed, an increase in H-wave amplitude has been observed for 5-11 min in the knee extensors following maximal voluntary contraction[9]. Acute changes in leg stiffness have previously been shown during endurance running[13] in response to a PAPE stimulus. It is therefore possible that an increase in musculotendinous stiffness may also have helped optimize the length-tension relationship of muscles, thereby reducing the magnitude and velocity of shortening, and therefore lowering energy usage[27]. Indeed, higher Achilles tendon stiffness is associated with superior RE[28], implying that an acute improvement in this quality may reduce the energy cost of running. Elevations in hormones such as testosterone[10] and plasma catecholamines[5], have also been reported immediately following a loaded conditioning activity, and are associated with improved physical performance. Finally, we cannot discount the possibility that the DJ provided a greater rise in muscle temperature compared to the C trial[8]. Given the low volume (six repetitions) of DJ used and the absence of change in metabolic and cardiovascular parameters this mechanism seems unlikely.

Although it is clear that endurance-trained athletes are capable of benefitting from a PAPE protocol[11], the phenomenon is more likely to occur in stronger individuals[4]. This is partly confirmed by findings in the present study as explosive strength capability, measured via a CMJ, was correlated ($r=-0.55$, $p=0.028$) with change in RE following DJ. This suggests that distance runners with greater levels of explosive strength are more likely to benefit from a PAPE protocol. In this study, DJ were performed from a height equal to a participants CMJ, therefore more explosive individuals received a higher stimulus than those who were less explosive. The possibility that differences in the absolute intensity of the stimulus applied explain the improvement observed in change in RE following DJ cannot be discounted. There are alternative options for determining an appropriate box height for performing DJ, which could be explored in the future. A box height that maximizes an individual's reactive strength index (the ratio between jump height in metres and contact time) has been proposed as a method of selecting DJ intensity[29]. This method has been shown to produce a DJ height approximately 10 cm lower than CMJ height in physically active males[30], thus it is unlikely a greater PAPE would have been observed using this strategy.

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

TTE at s$\dot{V}O_{2max}$ and end blood lactate were very similar between trials (ES: <0.2). Following a PAPE-inducing stimulus, a state of neuromuscular activation and fatigue coexist[6], therefore selecting a recovery time that allows fatigue to dissipate, yet a state of activation to remain, is essential to ensure a benefit is realized. In the present study, RE was measured 10 min after completion of DJ. The run to exhaustion then started 16-min after the DJ, thus any PAPE may have dissipated by this point in the trial. A similar response pattern was observed in a 20 km cycle time trial after heavy (5-repetition maximum) leg pressing exercise and a 10 min recovery[15]. Overall time was significantly quicker following heavy leg pressing, however this improvement was largely the consequence of a higher power output in the first 2 km of the time trial, with little difference observed in the remainder of the trial compared to a control condition[15]. As TTE at s$\dot{V}O_{2max}$ is influenced by different physiological factors compared to RE[2], it is also possible that this parameter does not benefit from a warm-up protocol of this nature. Predicted s$\dot{V}O_{2max}$ has shown improvements following a warm-up that included weighted vest sprints and a similar recovery (~20 min) to the present study. Thus, future research should investigate the efficacy of various loaded conditioning activities on key performance-related measures.

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

Conclusions

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

Practical applications

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

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

References

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

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

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

Table 1. Characteristics of study participants (n=17). $\dot{V}O_{2max.}$ = maximal oxygen uptake, sLTP = speed at lactate turn point, s$\dot{V}O_{2max.}$ = speed associated with maximal oxygen uptake, CMJ = counter-movement jump.

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

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 run to exhaustion at speed associated with $\dot{V}O_{2max}$. CI = confidence interval, DJ = depth jumps, C = control trial (body weight quarter squats), RPE = rating of perceived exertion (6-20 scale)

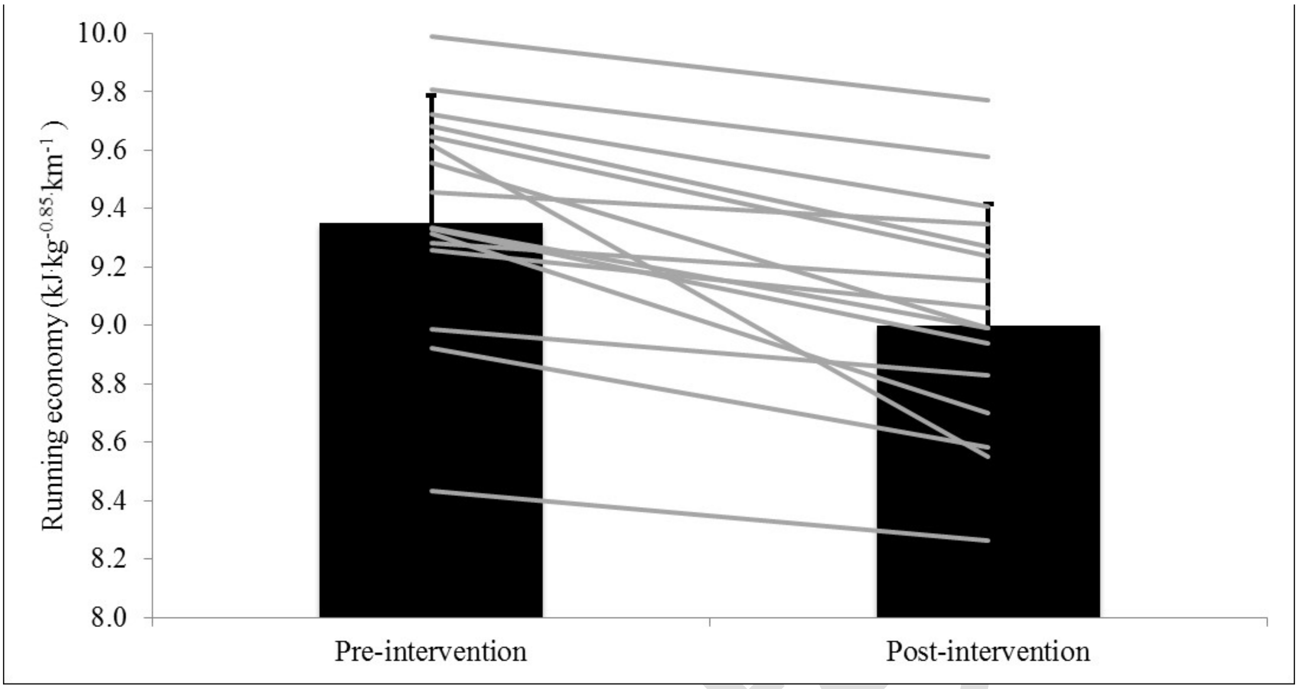

Figure 1. Mean±SD change and individual values (n=17) for running economy at 20%Δ below $\dot{V}O_2$ associated with lactate turn-point in the depth jump trial