The effects of resistance training on running economy – a review

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Running economy can be defined as the oxygen uptake required for a given velocity of submaximal running,[13] and is a better predictor of distance running performance than maximal oxygen uptake (VO_{2max}) in athletes who have a similar VO_{2max}.[14,23] Small improvements in running economy could, in theory, make the difference between winning and losing when the margins between athletes are small. Therefore, interventions to improve running economy are sought after.

Currently, the role that resistance training plays in promoting running economy is gaining a lot of interest, and it is the aim of this review to critically evaluate the limited data available on the topic. Several mechanisms have been proposed to explain how resistance training can improve running economy at the neuromuscular level, but it is beyond the scope of this paper to provide further insight in this area (please refer to reviews by Jung, 2003,[14] Laursen *et al*, 2005,[16] Saunders *et al*, 2004,[23]).

For the purpose of this review, 'resistance training' will refer to any training specifically designed to increase muscle strength, power or muscle endurance, irrespective of the stimulus of resistance.[14] Endurance running performance is defined as the capacity to sustain a given velocity or power output for the longest possible time and is therefore, heavily dependant on the aerobic energy system.[13]

Selection Criteria

Throughout the research phase it was apparent that this field has been neglected in terms of academic study, as only five original-research, peer-reviewed studies were identified looking at the effects of resistance training on running economy. None of the running-specific studies were excluded from the analysis because of the limited availability of research in the area. Additional studies investigating the effects of resistance training on other endurance type events were identified and will be referred to throughout, to provide further insight into the issues relating to resistance training and running economy.

Performance Analysis

Can resistance training improve running performance?

The effect of plyometric, explosive weight training and traditional weight training on running economy for each individual study shows that significant improvements in running economy (2.3–8.1%), can be gained by all 3 types of resistance training within a relatively short period of time (6–14 weeks) – *see Table 1*.

The study involving explosive weight training[19] *(see Table 1),* provided the most impressive gains in running economy, with slightly smaller gains seen in those studies that involved traditional weight training[12,17] *(see Table 1)*. Plyometric training appears to be only slightly less effective than traditional weight training on improving running economy[25,27] *(see Table 1).* It is worth noting here that the traditional weight training interventions tended to be longer than the plyometric studies, although frequency of sessions was relatively consistent. This suggests that gains in running economy through plyometric training is more effective than traditional weight training over the same period of time.

The interpretation of the findings should be viewed with caution given the small number of studies available for analysis, the difficulty in categorising some of the resistance training protocols due to a mixture of different types of resistance training being used[19] and the lack of clarity and detail relating to the intervention. In light of this, the main methodological limitations and the implications of these will be discussed below.

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	Endurance Training	*Resistance Training*	*Running Economy (RE)* *ml.kg^{-1}min^{-1}* *(unless otherwise stated)*
Spurrs et al (2003)	Normal endurance training: 60-80kmwk-1, unspecified intensity & training phase.	8 exercises 2 sets x 10 reps 2 sessions wk-1 for first 3 weeks, 3 sessions wk-1 for final 3 wks Intervention 6 wks	3 velocities: 12km.h^{-1}, 14kmh^{-1}, 16kmh^{-1} Av RE values +/- SDs for 3 running speeds. Values are Means +/- SDs: Group Pre-Training Post-training P %Change Exp 12kmh^{-1} 26.05 +/-4.11 24.30+/-3.68 ≤0.05 +6.7 14kmh^{-1} 33.35+/-5.15 31.23+/-4.27 ≤0.05 +6.4 16kmh^{-1} 41.96+/-6.14 40.22+/-5.43 ≤0.05 +4.1 Con 12kmh^{-1} 24.08+/-2.87 24.21+/-3.37 >0.05 -0.5 14kmh^{-1} 30.62+/-3.29 30.46+/-3.98 >0.05 +0.5 16kmh^{-1} 38.64+/-4.95 38.85+/-5.33 >0.05 -0.5
Turner et al (2003)	Normal endurance training: Min 10 miles wk-1, 3 sessions wk-1, unspecified intensity & training phase.	6 exercises 1 set x 5-25 reps 3 sessions wk-1 for Intervention 6wks	3 velocities: 2.23, 2.68 and 3.13m.s^{-1} (W); 2.68, 3.13 and 3.58m.s^{-1} (M) Av RE values (m.ml^{-1}.kg^{-1})** +/- SDs for 3 running speeds. Values are Means +/- SDs: Group Pre-Training Post-training P %Change Exp 5.14+/-0.39 5.26+/-0.39 ≤0.05 +2.3 Con 5.10+/- 0.36 5.06+/-0.36 >0.05 -0.8
Paavolainen et al, 1999	Total training vol: Exp: 8.4 hrs. wk-1, 9+/-2 sessions wk-1 Con: 9.2 hrs. wk-1, 8+/- sessions wk-1 32% & 3% training hours in Exp & Con replaced by sports specific explosive strength training Unspecified I, Post-competition phase	Various sprints (20-100m) and jumping exercises (4 exercises): Sets and reps not detailed. Leg press, knee-extensor flexor exercises, 30-200 contractions/ training session and 5-20 reps/set, load 0-40% 1-RM. 2-3 session.wk-1 Intervention 9 wks-1	2 velocities: 3.67m.s^{-1} and 4.17m.s^{-1} velocities Absolute values not given, results in table form only. RE in Exp and Con Groups did not differ pre-test, RE improved in Exp Gp (P≤0.05), no changes observed in Con Gp Exp. group improved approx. +8.1%
Johnston et al, 1997	Normal endurance training: 20-30miles wk-1, 4-5 days wk-1. F, I & D maintained 12 weeks prior to and 10 weeks during study. Training phase unspecified.	14 exercises: 7 exercises in Group A, 7 in Group B 2-3 sets, 6-20RM, 2 mins rest between sets 3 sessions wk-1 Intervention 10 wks	2 velocities: 214m.min^{-1} and 230m.min^{-1} Group Pre-Training Post-training P %Change Exp 214m.min^{-1} 41.7 39.9 ≤0.05 +4.3 230m.min^{-1} 44.5 42.8 ≤0.05 +3.8 Con 214m.min^{-1} 39.8 40.0 >0.05 -0.5 230m.min^{-1} 42.8 43.2 >0.05 -0.9
Millet et al, 2002	20hr.wk-1, running, cycling, swimming <70% VO$_{2max}$ in winter, non-competitive phase. Resistance training added after a 10wk pre-conditioning orientation phase.	6 exercises, 3-5 sets, 3-5RM 2 sessions wk-1 Intervention 14 weeks, periodised into 3-week periods	RE measured at below VT$_2$ (second ventilatory threshold) at 75% VO$_{2max}$ (velocity associated with VO$_{2max}$) and above VT$_2$ at △25% ≈92% VO$_{2max}$ – CR$_{75\%}$ and CR$_{\triangle 25\%}$ respectively) Group Pre-Training Post-training P %Change Exp CR$_{75\%}$ 193.6+/-4.3 180.2+/-20.0* >0.05 +6.9 CR$_{\triangle 25\%}$ 196.4+/-5.5 185.4+/-16.3** >0.05 +5.6 Con CR$_{75\%}$ 189.8 +/-13.1 203.2+/-20.2* >0.05 -7.1 CR$_{\triangle 25\%}$ 194.6+/-22.3 205.2+/-18.1** >0.05 -5.4 * P≤0.05 ** P≤0.05

*Table 1. Experimental and control training in studies of the effects of PLYOMETRIC, EXPLOSIVE WEIGHT TRAINING & TRADITIONAL WEIGHT TRAINING on endurance running performance. Please note that when looking at % change in running economy with resistance training, +ve changes denoted an improved economy whereas –ve changes signified a reduced economy. NSA= Not Statistically Analysed. ** Note that Running Economy measured in m.ml^{-1}.kg^{-1}*

Analysis of Training Studies

Specificity of training

All adaptations to training are specific to the stimulus applied,[15] so for optimal transfer of effects from resistance programmes to actual sports performance, there should be a high degree of task specificity with regards to movement patterns and force-velocity characteristics.[24] Plyometric training more closely mimics the movement speeds and mechanics of running than traditional style weight training.[6] Many of the plyometric exercises incorporated in the training studies detailed below[19,25] *(see Table 2)* have both a horizontal and vertical component, often involve unilateral foot strike patterns and typically do not require the undesirable deceleration phase associated with traditional weight training exercises.[15] The greater task specificity of these exercises, compared to the traditional strength exercises that usually only have a vertical component and are bilateral in nature, may explain why the study with a strong emphasis on power development, encompassing a range of explosive exercises including plyometrics, have produced the biggest gains in running economy. It may also partially explain why these explosive/plyometric studies have produced better gains in running economy over a much shorter intervention period *(see Table 1)*. However, it is interesting to note that out of all the studies involving plyometrics *(see Table 2)*, the one that includes drills with minimal emphasis on the horizontal component produced the smallest improvements in running economy.[27]

Despite the lack of mechanical specificity of traditional weight training programmes, there is some evidence that substantial gains in running economy can be achieved through a more traditional type strength programme[17,12] *(see Table 2).* Strength training can produce changes both at the muscular and neural level[26,14] to allow a better activation and co-ordination of the relevant muscles allowing a greater net force in the intended direction of movement. These studies imply that resistance interventions that tackle both increases in pure strength and explosive power may be more beneficial to running economy than either type of training in isolation.

None of the studies reviewed incorporated Olympic lifting into the programme. These lifts are reported to have a more optimal velocity profile compared to some strength exercises, and are thereby more effective in developing explosive power for running.[6] Triple extension of the ankle knee and hip[3] and stabilisation of the muscular core, are important aspects of running mechanics that influence running economy.[6] It seems logical therefore, that the Olympic lifts have the potential to affect running economy and should be evaluated in the future.

The degree to which specificity can impact outcome measures has been highlighted in a recent study involving trained cross country skiers.[10] Subjects performed a strength training programme, using apparatus that replicated a task-specific exercise for the upper body, 3 days wk -1 for 9 weeks (3 sets of 6 reps at 6-RM). Work economy improved by 22%. Perhaps greater consideration of specificity of exercises in the running studies may have produced much greater gains in running economy.

Quality of training

The efficacy of a resistance training intervention may rely heavily on the quality of an individual's training.[29] In all of the running studies reviewed, one study failed to report compliance to the intervention completely[19] and four used training diaries to log activities that were not statistically analysed.[17,12,25,27] Only one study definitely supervised the resistance training sessions,[12] one study did not[25] and the remaining three were unclear.[25,19,17] Athletes who did not give optimal focus and effort in the resistance sessions were unlikely to reap the most from the training,[29] implying that the extent to which resistance training may affect running economy may be largely under-reported in these studies.

Lag time

According to the fitness-fatigue paradigm,[23] an athlete's preparedness depends on two after-effects of training – fatigue and fitness. Therefore, maximising fitness improvements whilst minimising fatigue optimises preparedness. Since fatigue is a natural consequence of training, often adaptations are not fully observed until subsequent unloading periods.[22] In the 5 studies reviewed, post-test measures were completed almost immediately after the intervention. Therefore, the true magnitude of the effects on resistance training on running economy could have been missed.

Periodisation - macrocycle and microcycle considerations

Periodisation is defined as the "planned distribution or variation in training methods and means on a cyclic or periodic basis,"[22] with the primary aims being avoidance of overtraining and performing at peak or optimum levels at the right time.[7] For endurance runners, strength and power development can be hindered by endurance training due to the divergence of training induced muscle adaptations to improvements in strength or endurance,[2,8] which provides a dilemma for coaches in terms of programme design. There are four main points to highlight:

• Running is a relatively high velocity sport, so explosive type movements need to be trained in addition to force developing strategies such as strength training.[6] There is sufficient evidence from the running studies *(see Table 1),* to imply that all types of resistance training have their place in improving running economy. The optimal resistance training strategy to develop both the force and velocity components of power need to be determined and this may be the key for optimal improvements in running economy.

• There is a trade off between intensity and volume of training,[22] such that as one increases, the other must decrease to avoid overtraining. Endurance running is a high volume activity that typically involves a large proportion of high intensity work as the competitive period approaches.[21] In the study by Paavolainen and co-workers (1999), approximately one-third of the endurance training was replaced by resistance training and significant improvements in running economy were still observed *(see Table 1)*. This data is supported by a study involving competitive road cyclists[1] that showed increases in riding efficiency when 37% of the total endurance

STUDY	SPRINTS	PLYOMETRIC DRILLS	FIXED RESISTANCE EXERCISE	FREE WEIGHTS EXERCISE
			TYPE OF TRAINING	
Paavolainen et al, (1999) ↑ *8.1%*	Various sprints (20-100m)	Alternative jumps, Bilateral Countermovement Jumps, Drop Jumps Hurdle Jumps 1 legged, 5-Jump (5J) tests)	Leg Press Knee Extensor Flexor	None
Millet et al, (2002) ↑ *6.9-5.6%*	None	None	Hamstring Curl Leg Press Seated Press Leg Extension	Parallel Squat? Heel Raise? Unclear whether these are free or fixed in paper.
Spurrs et al (2003) ↑ *6.7-4.1%*	None	Squat Jump Split Scissor Jump Double Leg Bound Alternate Leg Bound Single Leg Fwd Hop Depth Jump Double Leg Hurdle Jump Single Leg Hurdle Hop	None	None
Johnston et al, (1997) ↑ *4.3-3.8%*	None	None	Group A: Knee Flexion Seated Press Rear Lat-pulldown Group B: Knee Extension, Seated Row Front Lat-pulldown,	Group A: Parallel Squat? Straight Leg Heel Raise Hammer Curl Weighted Sit-up Group B: Lunge Bent Leg Heel Raise Bench Press Abdominal Curl
Turner et al (2003) ↑ *2.3%*	None	Warm-Up Vertical Jumps Vertical Jumps One-Legged Vertical Jumps Vertical Springing Jumps Split-Squat Jumps Incline Jumps	None	None

Table 2: Specificity of Resistance Training Exercises (studies ordered by magnitude of effect)

↑ = improvement in running economy (%)
? unclear whether the exercise is a free weight or fixed resistance exercise.

training was replaced with resistance training. This supplementation of endurance training with resistance training may be the way forward in terms of programme design for endurance runners.

• Out of the five studies reviewed, two used the non-competitive phases[19,17] for their interventions, whilst the other three did not specify the phase of training. As the competition season approaches, there is increasing time spent on high intensity endurance training. At this time the athlete will already have completed a base level of training and subsequently will be able to support high intensity training to a greater degree.[21] For this reason the effectiveness of resistance training on running economy may be greater or less than reported if a periodised programme was performed.

• At the level of the micro-cycle, several factors have been highlighted that may affect the way the weekly programme is devised. Firstly, there is some evidence to suggest that running economy in well trained runners can be impaired for up to 8 hours following a resistance training session.[20] The implication of this is that if an athlete is performing multiple training sessions in the same day, then resistance training should be completed after endurance training. Secondly, intra-session order of strength and endurance training matters. In a study involving male sports students, improvements in endurance capacity was significantly greater when the endurance training preceded the strength training, in the same session, rather than the other way round.[4]

None of the running studies reviewed used a periodised approach to incorporate two seemingly incompatible training types to improve running economy. Nor did they account for differences in training effects associated by the sequencing of strength and endurance activities within the same session or between sessions within the same day.

POSITION	RUNNING EVENT Women's 1500m Min:secs (%)	Women's 5000m Min:secs (%)	Men's 5000m Min:secs (%)	Men's 10000m Min:secs (%)	Women's Marathon	Men's Maratho
Gold Medal	3:57.90s	14:45.65s	13:14.39s	27:05.10s	2h26:20s	2h10:55s
Silver Medal	3:58.12s (0.09)	14:48.19s (0.29)	13:14.59s (0.03)	27:09.39s (0.26)	2h26:32s (0.17)	2h11:29s (0.47%)
Bronze Medal	3:58.39s (0.21)	14:51.83s (0.69)	13:15.10s (0.09)	27:22.57s (1.06)	2h27:20s (0.83)	2h12:11s (1.05%)
4th place	3:59.05s (0.48)	14:55.52s (1.10)	13:15.35s (0.12)	27:25.48s (1.24)	2h28:15s (1.59)	2h12:26s (1.26)
5th Place	3:59.10s (0.50)	14:57.87s (1.36)	13:16.92s (0.32)	27:27.70s (1.37)	2h28:44s (1.99)	2h13:11s (1.89)

Table 3. Endurance running performance in the 2004 Olympic Games.

% = Percent improvement needed to gain gold medal winning time.
Available at: http://news.bbc.co.uk/sport1/hi/olympics_2004/athletics/results/ (Accessed 27th October, 2006)

Because of this, the true extent of the effects of resistance training on running economy are yet to be elucidated. However, Crawley (2001) recommends that if a coach is to incorporate explosive type plyometric training in programmes for endurance athletes they should "emphasise the development and maintenance of core strength and stability first, then allow for anatomical adaptation and the development of general and sport-specific strength prior to initiating explosive movements."

Significance of improvements

When working with high level athletes, it is important to decipher what degree of performance enhancement is necessary to improve medal-winning prospects. By looking at race times for various running events in the 2004 Olympic games *(see Table 3),* there is typically less than a 2% difference in performance times between first and 5th place. This means that potentially small improvements in running economy, possibly those that do not reach statistical significance in the literature, may be enough to make a real difference and a winning athlete. Given that well-controlled reliability studies have shown within subject variations in running, economy measures of between 1.5-5%,[23] rigorous experimental design is essential to determine the true magnitude of the effects of resistance training on running economy. Few of the running studies being reviewed have not documented controlling for confounding variables such as treadmill running experience,[19,25,27] footwear,[17,19,25,27] time of day of testing,[17,19,25,27] prior exercise,[17,19,25] and nutritional status.[17,19,25] Despite these limitations, the evidence suggests that a meaningful improvement in running economy could be realised by incorporating resistance training into an endurance programme, even in elite runners.[17]

Competitive race performance

The improvements in running economy observed with resistance training interventions have significantly improved 3-km (2.7%,[25]) and 5-km running performance (3.1%[19]). Although these tests were conducted in the field, they were not performed under race conditions. According to Hopkins and co-workers (1999), it is important to investigate the effects of interventions on competitive athletes in real or staged competition as this provides the only real dependable estimate of performance enhancement. Therefore, there is no guarantee that improvements in race times/running economy observed in the running studies reviewed will transfer into competitive success.

Subject Analysis

Table 4 documents the pertinent factors relating to training status of the subject and body mass changes that were observed in the running studies reviewed.

Athlete training status

The calibre of the athletes in the studies can influence the rate and extent of progression during a resistance training programme.[15] Individuals who are closer to their genetic limit have a smaller "window of adaptation" and require a more creative and varied programme design to prevent plateauing.[15] The exact nature and extent of weight-training experience of the subjects in the running studies has not been well documented, but it is implied that they do not have extensive experience of resistance training. Despite the small number of studies, one study[17] has used elite endurance runners, as evidenced by their high VO_{2max} values, i.e., around 70ml.kg^{-1} min^{-1},[23] and an improved running economy has still been observed. However, what remains to be studied is how much running economy continues to improve as resistance training experience increases.

STUDY	SUBJECTS		TRAINING STATUS		BODY MASS (KG) VALUES ARE MEANS +/-SDS	
	N	Age y (mean +/- SD)	History	VO_{2max} ($ml.kg^{-1}min^{-1}$) Values are Means +/-SDs	Pre-training	Post-training
PLYOMETRIC TRAINING						
Spurrs et al, 2003	17: 8 Exp (M), 9 Con (M)	25+/-4	Training history 10+/-6y, 60-80kmwk-1 No plyometrics in previous 3 months	Exp 57.6+/-7.7 Con 57.8+/-5.4	Exp 74.74 (2.94) Con 70.24+/-(6.47)	Exp 74.80+/-(2.85) Con 70.05+/-6.65
Turner et al, 2003	18: 10 Exp (6F, 4M) , 8 Con (4F,4M)	29 +/- 7	Regular runners, not highly trained	Exp 50.4+/-9.0 Con 54.0+/-7.2	Exp Men 70.3+/-14.2 Women 62.1+/-5.0 Con Men 82.1+/-17.0 Women 61.0+/-6.6	Not measured
EXPLOSIVE WEIGHT TRAINING						
Paavvolainen et al, 1999	22 (M): 12 Exp, 10 Con	Exp 23+/-3 Con 24+/-5	Elite X-country runners Training, h/yr: Exp532+/-27 Con 562+/-31 Training background: Exp 8+/-3 Con 9+/-4 Sprint/explosive strength times/wk: Exp & Con 0-1 Total training vol: Exp 8.4 hrs. wk-1 Exp 9.2 hrs. wk-1	Exp 63.7+/-2.7 Con 65.3+/-5.9	Exp 71.9+/-4.9 Con 70.2+/-4.2	Exp 72.3+/-4.4 Con 69.4+/-3.9
TRADITIONAL WEIGHT TRAINING						
Johnston et al, 1997	12 (F): 6 Exp, 6 Con	30.3+/-1.4	20-30 miles wk-1, 4-5 days wk-1, minimum 1 year. No regular weight training for min 3 months	Exp 50.5+/-2.2 Con 51.5+/-2.4	Exp 56.9+/-2.7 Con 51.5+/-2.0	Exp 58.2+/-2.6 Con 51.2+/-2.1
Millet et al, 2002	15: 7 Exp, 8 Con	Exp 24.3+/-5.2 Con 21.4+/-2.1	Elite triathletes. Total training y: Exp 7.0+/-2.6 Con 6.6+/-1.7 Vol (h.wk-1): Exp 20.5+/-3.8 Con 20.3+/-3.0	Exp 69.7+/-3.6 Con 67.6+/-6.4	Exp 67.4+/-8.8 Con 65.0+/-7.4	Exp 67.1+/-8.7 Con 64.09+/-6.8

Table 4: Athlete training status and changes in body mass with resistance training.

Body mass

Hypertrophy is often associated with strength training.[24] It is reasonable to assume that because body weight is supported in endurance running, gains in body mass would negatively affect performance, perhaps even if the change in body mass is associated with greater lean body mass.[23] *Table 4* illustrates clearly that body mass was not increased with any of the weight training programmes under review. Future periodised resistance and endurance training programmes will more fully investigate changes in body mass associated with concurrent training. However, it should be noted that typically ectomorphic endurance athletes are unlikely to significantly increase body mass.[28]

Conclusions

In summary, the research shows there are three types of resistance training that can improve running economy: explosive strength training including plyometrics, traditional heavy weight training and finally, simple plyometrics. However, there is much to learn in terms of how to periodise different modes of resistance training to gain the most benefit. Furthermore, the adaptation on running economy through resistance training needs to be evaluated under race conditions. Additionally, resistance training could be used to improve specific weaknesses in an athlete's physiology. Therefore future research should focus more on individual responses to resistance training. Only one of the studies reviewed[12] reported individuals separately and with such a small sample size (n=12), it was difficult to establish the range of improvements that can be realised.

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