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Endurance Training and Performance in Runners

Research Limitations and Unanswered Questions

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Abstract

The purpose of this review is to discuss several limitations common to research concerning running and, secondly, to identify selected areas where additional research appears needed. Hopefully, this review will provide guidance for future research in terms of topics, as well as design and methodology. Limitations in the research include: lack of longitudinal studies, inadequate description of training status of individuals, lack of confirmation of state of rest, nourishment and hydration, infrequent use of allometric scaling to express oxygen uptake, relative neglect of anaerobic power and physical structure as determinants of performance, neglect of the central nervous system, and reliance on laboratory data. Further research in a number of areas is needed to enhance our knowledge of running performance. This includes: body mass as a performance determinant, evaluation of methods used to measure economy of running, assessing the link between strength and running performance, and further examination of training methods. While the amount of research on distance running is voluminous, the present state of knowledge is somewhat restricted by the limitations in research design and methodology identified here.

Numerous studies of distance running have focused on training, determinants of performance and physiological profiling. Reviews of these topics are available elsewhere.[1-4] The purpose of this review is to discuss some of the limitations common to research on the topic and, secondly, to identify selected areas where additional research appears needed.

1. Research Limitations

1.1 Lack of Longitudinal Studies

The lack of longitudinal studies not only limits our understanding of the degree to which physiological changes continue to evolve over years of training but also how and when specific changes interact with performance improvement. Relatively few longitudinal studies have been conducted on runners.[5-9] Some physiological alterations occur quickly with training, such as increased plasma volume[10] and increased mitochondrial enzyme activity.[11] Maximal oxygen uptake ($\dot{V}O_{2max}$) can be significantly improved after only 3 weeks of training, with a one-half time for adaptation of 10.8 days.[12] However, other adaptations may not be optimised until years of training have accrued. For example, in elite cross-country skiers the percentage of slow twitch muscle fibre composition before and after 8 years of training increased 11% while training volume doubled in that period.[13]

The lack of longitudinal work limits understanding of the volume of training needed to optimise biological change and performance. Costill[14] determined that improvement in $\dot{V}O_{2max}$ reached a limit after a training volume of ~50–60 miles/week in runners. Additional mileage up to even 217 miles/week did not further improve $\dot{V}O_{2max}$. However, $\dot{V}O_{2max}$ was the only variable used to determine the effect of increased mileage. It is well known that significant performance improvement can occur without a change in $\dot{V}O_{2max}$,[5,15,16] so determination of how other variables respond to increased volume of training is needed. Costill's[16] study of swimmers also suggests that a volume threshold of training may exist. He observed that when collegiate swimmers reduced their training by half for 1 year in comparison to the volume in the 2 previous years that all individuals surpassed their performance in previous years and set personal records. However, it is unknown if the improvement was a consequence of heavier training volume in the previous 2 years. Absence of a control group precludes concluding that reduced training *per se* was responsible for the improvement. Wilmore and Costill[15] stated that the energy expenditure in training of ~5000–6000 kcal/week in distance runners may represent an ideal training regimen for most runners. However, data representing Finnish cross-country skiers indicate continued improvement in $\dot{V}O_{2max}$ with age and increased training volume from age 15–25 years.[13] Training increased from ~50 km/week at age 15 years to ~140–150 km/week at age 25 years. In contrast, relative $\dot{V}O_{2max}$ remains nearly constant in non-athletes after age 8–10 years.[17] Relative heart volume as well as $\dot{V}O_{2max}$ increased in a different group of elite cross-country skiers and was associated with increased training volume.[18] Elite athletes, perhaps because of their smaller mass and superior running or skiing economy, may be unique in their tolerance of musculoskeletal trauma associated with high mileage training, as well as their ability to benefit from it. Further investigation is needed in runners to determine what physiologic variables are associated with performance improvement over years of training and how much improvement is actually made.

Elite runners today generally train within a range of ~70–120 miles/week. Yet much, if not most, of the conditioning change probably occurs at far lower levels of training, particularly if intensity is high. Roger Bannister, the first sub 4 minute miler, reportedly ran only 5 days weekly for an hour performing interval training. Elite runners of the first half of the 20th century trained minimally by today's standards,[19] but their performances were impressive nonetheless. A point of diminishing returns from increased training volume has been suggested[19] and is supported by the training habits of champion runners years ago. Astrand and Rodahl[20] contend that the large training volumes of modern endurance athletes do not promote superior development of $\dot{V}O_{2max}$, compared with values achieved with far less work in the 1930–1950 era. However, other determinants of performance might be improved with high volume training and this subject needs further study.

The high volume approach to training prevalent today is associated with reaching elite performance status and faster running[21,22] but the performance benefit derived from this additional volume has not been adequately assessed experimentally. Lacking longitudinal data prevents identifying the specific physiologic adaptations associated with this progress. Athletes today train for years to make performance improvements of several percentage points. It would be interesting to know what specific physiological adaptations are made and the magnitude of these changes.

Short duration studies also limit the study of training periodisation. Little published work exists on this topic for distance running. A need exists to first determine if periodisation elicits better performance than a non-periodised approach. Secondly, if periodisation is found to be effective, then the training components that should be emphasised in various stages of training need to be determined. Traditionally, runners initiate training with a stage aimed at increasing volume or miles with little emphasis on speed, followed by stages that emphasise speed and improvement of $\dot{V}O_{2max}$, lactate threshold (LT) and running economy.[6] The soundness of the sequence has not been closely examined. In a survey study of 44 National Collegiate Athletic Association Division I cross-country teams, various types of training methods during specific stages of periodisation were correlated with performance at the end of the season.[6] Data included different types of running as well as supplemental forms of training such as strength work, plyometrics and stretching. While only descriptive in nature, such work provides at least some insight as to the synergistic and long-term nature of training. Conducting such research is a daunting task as participant retention, injury, etc. are problematical in that they limit statistical power. Having the patience to overcome such obstacles over several seasons and years perhaps explains the relative absence of such research.

Many studies have described the acute and chronic physiological effects of intermittent or interval training (IT) or compared IT with continuous training as to their effects on $\dot{V}O_{2max}$, LT, running economy, etc.[1,23-27] Because training programmes combine continuous and interval training, a comparison of one with the other provides limited information. The more important question is how to best combine the two training strategies over months and years of training. Little research information on this point is available because of the prevalence of short-duration studies. Carrying out longitudinal studies might be facilitated by using athletes at Olympic training centres and national development camps.

1.2 Inadequate Description of Training Status

Many studies fail to adequately describe the training status of the participants. It would seem important to know what training occurred in the months prior to testing. For example, runners currently or recently using IT would be expected to demonstrate limited physiological and performance response to an IT programme in contrast to lesser-trained athletes who have not previously used IT. Consequently, it is important to identify the training background of individuals to note the potential magnitude of the training effect. Similarly, the concept of periodisation is widely practised by coaches and athletes but researchers often seem to ignore its possible impact on their data.

The training response should be examined in relationship to previous training in order to distinguish between the effects of the two. This information can easily be described in published work and it should aid interpretation of results.

1.3 Lack of Confirmation of State of Rest, Nourishment and Hydration

Confirmation that testing was performed with athletes in a rested, well-nourished and hydrated state is omitted in most studies. Glycogen stores[28] and hydration[29] status are known to affect performance and consequently need to be controlled in studies, particularly when using longer performance tests. Knowledge of these factors is well known, yet few studies confirm that athletes actually refrained from serious training effort in the days prior to testing. Similarly, hydration status is rarely mentioned in the methods of studies yet it is known to affect heart rate (HR) and blood values. It may also affect the slow component of oxygen uptake ($\dot{V}O_2$). It is common to read in published articles that individuals were encouraged to avoid strenuous exertion the day before testing and to avoid eating several hours beforehand, but additional information about these points is usually omitted. Did the participants actually follow the instructions provided? If not, was testing rescheduled? In studies where nutritional status and hydration are particularly likely to influence test data, measurement of urine specific gravity and the use of a 3-day dietary recall would seem helpful. These procedures do not involve much cost or participant time. This information would be useful in the interpretation of studies and should be described in published work.

1.4 Limited Use of Allometric Scaling to Express Oxygen uptake

Most research on running includes measurement or discussion of $\dot{V}O_{2max}$ or peak oxygen uptake ($\dot{V}O_{2peak}$). The variable is typically expressed relative to body mass (ml/kg/min) to equate athletes of varying mass. However, data from the 1960s,[20] as well as more recently, clearly indicate that linear scaling does not adequately adjust for body mass. Instead of an exponent of 1.0, exponents actually vary between about 0.67 and 0.75.[30-33] The magnitude of error in using an inappropriate exponent is sizeable when mass varies considerably. For example, Astrand and Rodahl[20] assessed $\dot{V}O_{2max}$ in individuals ranging in mass from 55–93kg. Scores were expressed as L/min, ml/kg/min (exponent of 1) and ml/kg/min using an exponent of 0.67. The resulting correlations between body mass and $\dot{V}O_{2max}$ were 0.86, –0.69 and –0.06, respectively. Linear scaling obviously is limited in adjusting for mass, while allometric scaling using an exponent of 0.67 effectively removed the effect of mass such that the correlation was close to zero. The validity of the 0.67 exponent is sound in samples where body mass, age, height and training status are similar, but an exponent of 0.75 is suggested in more heterogeneous groups.[32]

Nearly all research since the concept of allometric scaling was first applied to the discipline of exercise physiology and science has used linear scaling to express relative aerobic capacity. Even today, nearly all published work in the field is expressed linearly. Clearly, a change in expression of $\dot{V}O_2$, both maximal as well as submaximal values, needs to be made. Linear scaling makes heavier runners appear to have lower values of $\dot{V}O_{2max}$ yet higher levels of running economy since submaximal $\dot{V}O_2$ is artificially lowered. The influence of this error on running research is problematic.

What errors are made in interpreting data not expressed allometrically? The values for $\dot{V}O_{2max}$ in runners with low body mass, which is the norm for trained runners, are inflated. The opposite is true for heavier runners. Elite male Kenyan runners typically weigh ~14kg less than Caucasian runners[34] and therefore their $\dot{V}O_{2max}$ scores are considerably inflated using the linear standard. Interestingly, the $\dot{V}O_{2max}$ data for elite Kenyan runners, expressed linearly (ml/kg/min), is similar to values for European and American runners. Consequently, the performance dominance in recent years of Kenyan runners does not appear to lie in a superior $\dot{V}O_{2max}$. When comparing African runners, such as Kenyans, to elite non-African runners, their economy appears to be superior,[35] although one would expect to find them less economical with $\dot{V}O_2$ expressed linearly.

With greater frequency today, elite athletes are tested in the laboratory and then advised to make adjustments in training. The validity of making such modifications is somewhat limited when expressing $\dot{V}O_2$ linearly. A lean athlete with a larger skeletal structure and mass might be thought to need greater emphasis in training to improve $\dot{V}O_{2max}$. In pursuit of this goal, both athlete and coach may be frustrated by the inability to make such a change. Increasing the intensity or volume of training in search of an elusive goal may lead to overtraining. Similarly, a smaller runner whose running economy is noted to be less than expected might be fruitlessly directed to emphasise training to improve what appears to be a deficit. All in all, attempts to apply laboratory data to training are tainted because of how $\dot{V}O_2$ is expressed. Furthermore, since so much laboratory data is based on $\dot{V}O_2$ (e.g. $\dot{V}O_{2max}$, velocity at $\dot{V}O_{2max}$ and LT, economy), the validity of applying these data to the training of athletes is somewhat flawed if using an exponent of 1.

1.5 Relative Neglect of Anaerobic Power and Physical Structure as Determinants of Performance

The most commonly used variables in research aimed at identifying determinants of running performance have been measures of aerobic function such as $\dot{V}O_{2max}$, velocity at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$), LT and running economy. While these variables are able to predict performance and explain variance quite well,[36] other factors that undoubtedly play a role in performance are usually not addressed. Noakes[19] suggested that endurance performance may in part be determined, and even limited, by muscle power. In recent years, measures of anaerobic power such as short sprints and jumps have been shown to add considerably to the explained variance in distance running performance.[36-38]

In addition, physique and somatotype seem to be worthy of continued investigation but currently are not usually included in the battery of testing to predict performance. Somatotype and physique of Olympic runners are distinct from many other athletic populations.[39] For example, distance runners are leaner and more ectomorphic than many other athletes,[40,41] but the importance of these physical traits in performance has not been thoroughly studied. In heterogeneous samples of runners, somatotype contributes moderately to explained variance of running performance.[42] Observation of elite African runners suggests a definitive prototype in which body mass is minimised and facilitated by a somatotype that may be more ectomorphic than is typical of Caucasians, e.g. very thin legs. It would be interesting and insightful to determine the variance in performance explained by physical structure when combined with indicators of aerobic and anaerobic power as well.

1.6 Relative Neglect of the Role of the CNS

The model for much of the research on distance running has assumed that the limitation to endurance performance is the capacity of the heart to pump a large volume of blood to active muscle tissue. Consequently, the research in general has emphasised the influence of training on the heart, vasculature, $\dot{V}O_{2max}$, LT and other indicators of the capacity to transport and utilise oxygen. The role of other physiologic systems, including the CNS, has been neglected. Yet substantial evidence now indicates that the CNS is involved in fatigue and hence performance.

An alternative model of endurance performance proposed by Noakes,[43] and supported by recent work, suggests the importance of the CNS in understanding the physiology of training for endurance performance. Kayser et al.[44] noted that integrated electromyographic (IEMG) activity was reduced at peak exercise while at high altitude, but was increased with supplemental oxygen. Consequently, they concluded that the CNS may be involved in fatigue.[44] Further supporting evidence for the role of the brain in endurance performance is the report of significant deterioration in IEMG over time in 100km cycling time trials.[45] This change was paralleled by reduced power output during stochastic bouts of high intensity exercise. HR increased during the time trial supporting the idea that the athletes did not consciously reduce their effort. The fact that IEMG decreased ruled out the possibility that muscle activity was reduced because of muscle glycogen depletion. Typically, neural recruitment would be expected to increase with glycogen depletion. The authors concluded that the results support the existence of a central governor that subconsciously reduces muscle recruitment during prolonged exercise.

These findings support the idea that cerebral output may be a source of fatigue and hence a determinant of endurance performance. Additional work that concurrently examines the role of multiple systems appears justified. The activity of the brain's input and output during strenuous endurance performance should be included in work examining various exercise intensities and durations, and environmental conditions. A fuller understanding of fatigue may have implications for endurance training and performance.

1.7 Reliance on Laboratory Data

Laboratory-based testing may be limited in eliciting maximum performance. Foster et al.[46] demonstrated greater physiological responses when individuals were allowed to select their own pattern of testing rather than being assessed via a typical incremental protocol. The former protocol leaves the athlete in charge of determining a pace and duration that is similar to actual competition. Similarly, athletes tested during simulated competition outside the laboratory exhibited higher HR than when tested in the laboratory.[47] Competition elicits an ability to tolerate greater discomfort and for longer periods. In training and in the laboratory, the same level of exertion is difficult to tolerate. Laboratory data are therefore probably something less than the actual maximum but the extent of the difference is not known for most variables. Perhaps most laboratory data should be referred to as 'peak' values rather than maximum, which is the nomenclature some prefer to use in expressing the highest level of $\dot{V}O_2$ obtained in a graded exercise test. Current technology, using portable equipment, allows the measurement of HR and $\dot{V}O_2$ while running on the track and road, which in turn increases the probability of attaining maximal values. It also provides knowledge of the magnitude of difference in laboratory versus field data. Future work should attempt to use technology that permits assessment outside the laboratory.

2. Unanswered Questions

Several areas of research on running have not been widely or directly studied. Also, no firm conclusions can be made on several topics because of equivocal findings. These unanswered questions appear to be fruitful areas for future work and are highlighted here.

2.1 Why Are Elite Runners so Small?

Observation of non-elite runners at most road races in the US suggests that body mass is a determinant of running performance. Even at this level the winners and top finishers are usually rather small people. At the elite level the difference is striking. In a study of elite South African runners, African athletes were 168cm in height and weighed 61kg while elite Caucasian runners were 180cm and 70kg.[34] Do smaller stature and mass provide an advantage? And if so, what are the mechanisms involved? Surprisingly little research has addressed this question.

Several factors may explain the advantage of low body mass in running. Ground reaction forces while running are reduced in lighter runners than heavier ones. Attenuating shock may be a requisite to maintaining the high mileage/high intensity characteristic of today's elite runners and athletes of limited mass; this may be why they have an advantage. Elite African runners reportedly run a much larger percentage of their mileage doing quality work than their western counterparts.[34] Coaches often prescribe intense or quality running as a percentage of the athlete's weekly mileage. For example, Daniels[48] recommended that speed training comprise ~5% of weekly mileage, training to improve $\dot{V}O_{2max}$ ~10% and training to elevate LT ~12%. The rationale for such recommendations is based on injury avoidance, as well as overtraining. It would be interesting to compare the rate of athletic injury and overtraining in African runners and Western runners. The more physically demanding lifestyle, beginning in childhood, that includes large amounts of walking and running over rugged terrain[49] may provide a foundation of conditioning that allows them to withstand greater demands when structured training ensues. Reduced ground reaction forces while running may also be involved.

Another possible advantage related to the limited mass of the elite runner is heat accumulation; this is largely the function of heat production versus heat dissipation. Heavier runners produce and store more heat at a given submaximal running velocity.[50,51] Furthermore, in a recent report, the correlation between heat storage and body mass was increased at higher environmental temperatures. Also, immediately following a 30 minute submaximal run, the decrement in 8km race pace was significantly and negatively related to body mass ($r = -0.77$, $p < 0.0004$).[51] The apparent thermodynamic advantage of lighter runners may allow them to run more intensely or longer before reaching a limiting core temperature. A core temperature of 39.5°C has been posited as a threshold for fatigue. This threshold temperature appears to be the same for runners of various fitness levels. Fitter or more gifted runners can simply run longer or faster before reaching this temperature.[52] As temperature rises while running, metabolism is prompted upwards which is reflected by a rise in $\dot{V}O_2$ and HR. Heavier runners generate more heat, and therefore a greater oxygen cost of maintaining a given pace, and would reach the critical 39.5°C temperature sooner. Runners with very small mass, such as the Kenyans, would be less heat-challenged. This would be advantageous in competition, but may also allow training loads to be increased in volume and intensity, and especially volume at high intensity.

Recent work indicates that altered cerebral function, rather than muscular factors, may be associated with fatigue during prolonged work in the heat.[53-55] In well-trained cyclists, electroencephalogram activity over the prefrontal cortex, which is involved in the initiation of voluntary movements, decreased as core temperature rose. Concurrent electromyographic activity over time indicated no impairment of neuromotor recruitment and discharge rates.[55] Consequently, evidence exists that fatigue associated with hyperthermia may be due to reduced cerebral activity rather than peripheral factors. Further work is justified to examine the role of the brain as a factor in the limitation to exercise.

Why is heat production and storage higher in larger runners? The answer may lie in the allometric relationships of heat production and dissipation to body mass. Heat production would seemingly increase with mass, which is a 3-dimensional concept since height, width and depth are all involved. Heat dissipation, however, appears to be related to body surface area, which is 2-dimensional. Thus, increased mass during work would theoretically increase heat production exponentially placing larger individuals at a disadvantage in sustaining high-intensity exercise. Further clarification regarding these points is needed to better understand the limits possibly imposed by mass.

2.2 How Sound is the Measurement of Running Economy Currently Used?

Running economy affects running speed in competition and so is an important determinant of performance.[36] It is usually measured in the laboratory as the relative oxygen cost (ml/kg/min) to run at a given submaximal velocity. However, using oxygen cost to assess economy may not be entirely sound. First, actual mechanical work performed is unaccounted for, which in part invalidates the procedure. Also, substrate utilisation is not factored into the calculation of the energy cost of running. It has been suggested that fitter runners with high maximum oxygen uptakes might be able to metabolise larger amounts of fat simply because of possessing a greater reserve of oxygen transport and utilisation. Several investigations reported a negative correlation between $\dot{V}O_{2max}$ and economy in trained runners.[56,57] It seems unlikely that fitter or more genetically gifted runners would tend to be more wasteful of their oxygen uptake than others. A higher, rather than lower, submaximal $\dot{V}O_2$ may be beneficial in long duration events such as the marathon if it is associated with a greater utilisation of fat as a substrate, which would spare the limited muscle and liver glycogen stores. Consequently, measurement of economy as presently done is problematical and needs to be re-examined. Perhaps measurement of work could be accomplished more accurately than in previous years through the use of accelerometers and force plates which are more readily available to researchers today. Collaboration of biomechanists and exercise physiologists would be fitting. The problem of substrate utilisation as a confounder also needs to be dealt with. Perhaps the oxygen cost could be corrected for substrate utilisation by expressing economy as kcal of energy expenditure rather than oxygen. Thus, the economy of runners might be compared in units of kcal per joule of work performed or kcal per unit of velocity. An equation estimating the mechanical power of running has been developed and includes respiratory exchange ratio (RER) in the calculation.[58] Another alternative when making statistical comparisons of economy among groups would be to make an adjustment using analysis of covariance using RER as a covariate.

2.3 Why is Running Economy so Variable Even in Trained Runners?

Running economy appears to be multifactorial, with possible determinants including skill or biomechanics, training velocity, muscle fibre type, $\dot{V}O_{2max}$, substrate utilisation, muscle power and flexibility. This complexity may explain its wide variability even in trained runners.[5,59] For example, Svendenhag and Sjodin[60] found that economy varied by as much as 30% in trained runners. If economy was largely a matter of motor learning, then the relatively simple skill of running would seemingly be mastered by more runners, which would reduce the variability of economy. Some work has examined the biomechanics of running but the conclusions are not supportive of biomechanics being a primary determinant of running economy. Runners are often advised to shorten their strides to improve economy,[19] yet some research indicates that chronic training increases stride length and reduces stride rate.[8] Biomechanical variables such as arm carriage, vertical oscillation of the centre of gravity, stride rate and length, Q angle and kinetics of the thigh, foot and ankle would be logical candidates for study. Anecdotally, great runners seem to be noted for their minimum vertical oscillation.[19] In a study of runners matched for $\dot{V}O_{2max}$, it was reported that the vertical force in slower runners was about twice that of faster runners.[61] Our knowledge of the influence of biomechanics on economy today is limited and a collaborative effort between the biomechanist and exercise physiologist is needed.

Running economy appears to be speed-specific, so that a marathoner tends to be more economical at marathon pace than 800 and 1500m specialists, while the opposite is true at middle distance pace.[31] Thus, comparison of economy in runners must consider the distance and velocity specifically trained for. Comparing marathoners and milers at a submaximal speed below LT favours the marathoners. Another means of demonstrating enhanced running economy with training is improved $v\dot{V}O_{2max}$ with little or no change in $\dot{V}O_{2max}$. Jones and Carter,[2] in a recent review, reported several studies documenting such improvement in elite as well as untrained runners. These works suggest that the most meaningful measurement of running economy should occur near or at race pace rather than some arbitrary submaximal velocity, which is commonly done. For marathoners, submaximal velocity similar to race pace would seemingly be most appropriate while velocities as high as

$v\dot{V}O_{2max}$ would be more pertinent for 1500, 5000 and 10 000m specialists.

Another determinant of economy may be muscle fibre type. Athletes with an abundance of type I fibres appear to produce less lactate with an associated lower oxygen cost.[62] Lack of flexibility is also associated with better running economy.[63,64] The suggested mechanism is greater storage and utilisation of elastic energy during the stretch-shortening cycle while running. The greater contribution of elastic energy in theory would reduce the oxygen cost of running. It has also been suggested that tightness of the hips and trunk may aid in stabilising the pelvis and spinal column, thus requiring reduced muscle contraction and energy expenditure.[63] However, any conclusion regarding the flexibility-economy relationship should be viewed with caution as no experimental studies have been conducted to demonstrate a cause-effect relationship. As runners log more mileage they may become more skilful, convert more type II fibres to type I and also lose flexibility. The integrated role of each factor in affecting economy is unknown.

The superiority of the African runner in part seems to be explained by economy.[35] Trained, but not elite, African and Caucasian runners were compared while running at current 10km race pace. The two groups were matched for body mass and 10km performance. The African runners were 5% more economical, ran at a higher percentage of $\dot{V}O_{2max}$ (92 *vs* 86%), yet their lactate level was only slightly higher (5.2 *vs* 4.2 mmol/L; $p > 0.05$). Mechanisms explaining these differences are unknown but superior lactate removal and mitochondrial enzyme capacity were suggested.

2.4 How can Running Economy be Improved?

Training improves economy through several mechanisms. Some studies have indicated that economy improves with increased mileage and age.[57,65,66] High-intensity training has also been reported to be effective in eliciting improved economy.[65,67] Improved economy has been demonstrated in several short-term studies.[67,68] Running in and of itself may improve economy by reducing the cost of breathing,[67] converting type II fibres to type I fibres and tightening muscles of the hips, which may facilitate using more elastic energy in these muscle groups.[63] Plyometric training, sprinting and explosive weight training have also been shown to improve economy.[37] Consequently, the means of improving economy appear to be as diverse as the number of factors affecting it.

Researchers interested in studying economy should ensure that athletes are well rested when tested. Some of the energy generated while running is derived from the elastic component in muscle, tendon and fascia, particularly at higher velocities.[69] Muscle fatigue and soreness are accompanied by damage to contractile proteins, as well as these soft tissues. Hence, if an athlete is tested for running economy the day after strenuous exertion, then additional motor units and muscle fibres would probably be recruited during the running test and elevate $\dot{V}O_2$. Shoe weight should be noted in studies assessing economy, as small differences in weight alter the energy cost measurably.[70] In studies assessing changes in running economy shoe type and weight should be standardised. Often in the literature little or nothing is stated regarding whether or not any steps were taken to assure that all tests were conducted in a rested state. Such information should be the norm in published work on the subject.

In summary, measurement of running economy by measuring submaximal $\dot{V}O_2$ was adopted and used because of its simplicity in data collection and interpretation. However, research is needed to quantify the work actually done while running in order to better understand economy. Also, much of the work on running economy was carried out before recognition of the slow component of $\dot{V}O_2$. Hence, values reported in the literature on the oxygen cost of running may reflect the contribution of the slow component in varying degrees, depending on the intensity and duration of the running speed used. Future work should consider the slow component of $\dot{V}O_2$ in the design and measurement of oxygen cost. Lastly, more work is needed where the design includes assessment of multiple variables such as fibre type, biomechanics, training variables, physical structure, flexibility, etc., such as the study by Pate et al.[57] This type of comprehensive analysis will be useful in determining how much variance is explained by specific variables.

2.5 Does Strength Training Enhance Run Performance?

Strength training seems to be under-utilised in the training of runners compared with other endurance athletes such as swimmers, cyclists and cross-country skiers. Many elite runners attained this status without ever resorting to strength training. The disparity in the use of weight training in runners may stem from the complexity of running as a neuromotor task. Cycling isolates the great majority of the work to the muscles of the hip and thigh. In contrast, running requires more dynamic upper body involvement and trunk rotation, in addition to recruitment of the primary movers in the hip, thigh and calf. The relative simplicity of cycling may facilitate designing and finding weight training exercises that mimic the lower extremity motions of cycling. Most weight training exercises for the lower extremities, particularly those using machine weights, may limit mimicking the movement of running. Traditional exercises, such as knee extension and knee flexion, are open kinetic chain motions that are dissimilar to running mechanics. Even closed chain kinetic exercises, such as the squat and power clean, may be limited in specificity as they are performed with both feet on the ground rather than one foot as in running. Traditional weight exercises are also performed slowly in contrast to the relatively high velocity of distance running. Thus, traditional weight training exercises appear to offer limited likelihood of performance enhancement. Exceptions may occur in individuals with limited basic strength, such as seniors and youth.

Resistance training for swimmers emphasises specificity of training. Exercise equipment, such as a swim bench, were developed to facilitate building strength in the prone position while mimicking the mechanics of various strokes. Pulleys with weights have been used for years by swimmers and allow mimicking of swim strokes. In cycling,[71] swimming[72] and cross-country skiing[73] research indicates that strength training enhances performance. In cross-country skiing the importance of upper body and torso power is demonstrated by the observation that elite skiers are more powerful in the upper body than non-elite skiers. Recommendations from this research indicate that in cross-country skiing more emphasis should be given to upper body strength/power training.[73] The lack of supporting evidence for strength training in running is in striking contrast to that for the previously mentioned sports. However, it seems unlikely that running would be unique in not being facilitated by strength and power enhancement. The reason may lie in the complexity of the motor pattern as discussed previously. Perhaps performance enhancement in running only awaits the development of training exercises that truly are specific to running. Research is clearly warranted here.

A widely cited source demonstrating that strength training might aid running performance observed that while weight training did not alter $\dot{V}O_{2max}$, it did allow a longer duration of effort at $\dot{V}O_{2max}$.[71] This specific improvement would seemingly have application to middle distance events such as the 800 and 1500m events. However, individuals in the study were untrained, which may limit application to the trained runner. Other studies indicate that sprint time and peak torque at high velocity (400 degrees/sec)[38] and anaerobic power[36] explain a good portion of the variance in distance running performance in trained runners, although not as well as measures of aerobic power such as velocity at LT (vLT)/velocity at ventilatory threshold and $v\dot{V}O_{2max}$.

Recent investigations have demonstrated that plyometric jump performance is a meaningful predictor of distance run performance,[74] and that plyometric training improves distance run performance.[37,75] Performance in 5000m run time improved by ~30sec in experienced well-trained runners, although training volume was reduced.[37] Stride length and $\dot{V}O_{2max}$ remained unchanged, but foot contact time on a force plate decreased 7%. The advantage of this type of training for running is that it allows training movements that are very similar to running. Running is, by definition, a series of hops, so logically, hopping and skipping activities closely resemble running. Furthermore, the velocity of movement is similar to running. By increasing the rate of force development, stride rate or length might be improved. A small improvement in either variable across the many steps taken while racing might result in improved running. Consequently, it seems logical that plyometric training, incorporating movements similar to running, offers good potential for resistance work to aid run performance.

The volume and intensity of weight training probably needs to be limited so that the development of muscle mass is minimised. Yet, some additional muscle mass may not be detrimental as long as it contributes to improved power and shock absorption.

Sprinting, striding, short runs up hills or steps and plyometrics are likely useful training adjuncts to enhance performance because of the similarity in velocity and movement pattern to distance running. The fact that these methods have been traditionally used provides further support that they seem to contribute something unique. These techniques may improve or at least maintain muscle power, which is usually reduced as a consequence of endurance training.[76] Furthermore, they do so without apparent gain of muscle mass. Consequently, application of typical strength training programmes in runners who previously or concurrently use these techniques may not provide enough specific strength and power development above that attained as a result of speed work, hills and plyometrics. More research is needed in this area.

2.6 What is the Optimal Training Stimulus for Improving Aerobic Function and Performance?

Training intensity used for athletes usually falls in the range of ~70–100% $\dot{V}O_{2max}$.[1,77] Obviously, the volume of work is greater when intensity is in the lower portion of this range. Because both intensity and volume are stimuli for improving aerobic fitness and performance, researchers for years have been curious as to what combination of the two variables might be optimal. The two variables are inversely related so that maximising one is done at the expense of the other. Noakes[19] concluded that an important benefit of higher mileage training is to improve economy which permits running at a faster velocity. However, fraction utilisation is not improved.[21]

Some suggest that training at LT is an optimal compromise as it allows a good combination of volume and intensity.[78,79] Also because vLT is well correlated with performance, it appears to be a particularly beneficial training intensity.[38] Others believe that the slowest running velocity that elicits $\dot{V}O_{2max}$ may be the optimal training stimulus.[80] However, it remains unresolved whether it is better to exercise at a high but submaximal fraction of $\dot{V}O_{2max}$ for a longer period or to exert at $\dot{V}O_{2max}$ but for a shorter duration. In evaluating research on the topic it should be noted that physiological effects may not coincide with improved performance. For example, performance is known to change fairly dramatically even when no alteration of $\dot{V}O_{2max}$ occurs.[5,69]

Scandinavian researchers compared various work intensities and work-rest ratios for their effect on $\dot{V}O_2$ and blood lactate concentration (BLC).[20] Essentially, as long as the work bout was the same length or longer than the recovery period, then $\dot{V}O_{2max}$ could be reached and maintained for a longer duration than possible during continuous exercise at a work rate or velocity that elicited $\dot{V}O_{2max}$. Duration and spacing of the work and rest periods were crucial in determining the associated $\dot{V}O_2$. For example, alternating 10 second work intervals with 5 second rest periods allowed the highest $\dot{V}O_2$ to be reached. Increasing the rest to 10 seconds dramatically reduced the $\dot{V}O_2$. In addition, $\dot{V}O_2$ remained high during the brief rest periods.[24] Surprisingly, blood lactate level was kept much lower than when work was continuous. It was believed that the muscle phosphagens supplied much of the substrate during intermittent work and that myoglobin supplied additional oxygen, which reduced the load on the glycolytic pathways resulting in lower lactate levels. Thus, a greater duration of time spent at $\dot{V}O_{2max}$ was allowed. Longer work bouts, such as 30 and 60 seconds alternated with rest periods of equal length, failed to elicit equivalent $\dot{V}O_2$ values yet BLC was quite high.[24] A large number of studies (reviewed in Billat[1]) conducted since this period support the value of IT in improving various parameters of aerobic fitness as well as performance. However, this research only substantiates that some IT is needed to optimise performance. It does not address the question as to how much is needed and how it should best be blended into the typical training regimen. Only longitudinal work will permit an answer to this question.

Recent work has shed new light on the topic, which may be useful in solving the problem of diminished training volume when intensity is raised. DeMarie et al.[81] studied $\dot{V}O_2$ kinetics in middle-aged runners. They noted that running at a pace midway between LT and $v\dot{V}O_{2max}$ (v50% delta) slowly raised the $\dot{V}O_2$ during the run until it equalled and then surpassed $\dot{V}O_{2max}$, as measured in an incremental test to exhaustion. Individuals performed interval training with a work-rest ratio of 2 : 1. Duration of the work bouts and recovery jogs individualised for each participant lasted between 4–6.5 minutes and 2–3.25 minutes for the work and rest periods, respectively. The mean $\dot{V}O_2$ actually reached during an intermittent run at v50% delta was 64 ml/kg/min, while the mean peak value achieved in the incremental test was 56 ml/kg/min. $\dot{V}O_{2max}$ peaked at 61 ml/kg/min during continuous running at v50% delta. BLC after running at v50% delta intermittently and continuously were 6.5 and 7.8 mmol/L, respectively. Total duration of time at or above $\dot{V}O_{2max}$, as measured in the incremental test, was extended from ~5 minutes during continuous running to ~10.5 minutes in the IT format. The $\dot{V}O_2$ slow component explained the slow rise in $\dot{V}O_2$ that eventually reached supramaximum values. The results of this study are provocative in addressing the problem of how to achieve volume and intensity. The fact that $\dot{V}O_{2max}$, attained in a graded test, was not only achieved but was sustained longer, and at a lower BLC, theoretically makes this type of training uniquely valuable. The fact that it can be achieved while running at a pace slower than $v\dot{V}O_{2max}$ suggests less ground reaction force and with it less likelihood of acute, as well as chronic, injury. The reduced lactate level may indicate a lesser degree of physiologic stress that, if accompanied by lower ratings of perceived exertion, may be important in terms of reducing the occurrence of overtraining. On the other hand, the physiologic benefits of slower running may be limited as the main goal of all training should be increased race pace. Further work relating this training to success in competition is needed. It would also be useful for future studies on this topic to examine training-related factors such as ratings of perceived exertion, markers of stress (e.g. catecholamines, cortisol) and overtraining (e.g. Profile of Mood States, hormones and HR variability) and injury rate. These factors seem to mark the upper limits of training and it would be useful to compare how various training regimens challenge these limits.

It is still unresolved whether or not a better performance results from training at v50% delta compared with the actual $v\dot{V}O_{2max}$ attained in a short incremental test. Does the lower velocity limit improvement of economy at higher running velocities, such as 1500 and 5000m, which are run at paces above or very close to $v\dot{V}O_{2max}$? The slowest pace to achieve $\dot{V}O_{2max}$ may be beneficial in some aspects of training, such as mitochondrial mass and enzymes and perhaps would be more valuable to longer events, while use of the highest speed at $\dot{V}O_{2max}$ may be more beneficial at shorter distances where race pace occurs at or above $v\dot{V}O_{2max}$. Also, development of anaerobic capacity and tolerance to pH would probably be better enhanced with training at the higher speed. Consequently, while several new concepts dealing with IT have been tested, further work is needed to identify whether or not the various types of training to elicit $\dot{V}O_{2max}$ have specific applications to various race distances. To the author's knowledge, no work has been done testing this hypothesis.

Intermittent training also has implications for assessing $\dot{V}O_{2max}$ in athletes. Peak values for $\dot{V}O_2$ in the DeMarie et al.[81] study were lowest during an incremental test, intermediate during a continuous run at v50% delta and highest in the intermittent exercise session. Because the differences in these values were statistically significant, but also meaningful, laboratory test protocols might use an intermittent approach at v50% delta in order to capture the effect of the $\dot{V}O_2$ slow component. $\dot{V}O_{2peak}$ was 12% higher in the intermittent exercise than the incremental test. This value exceeds the seasonal variation in trained runners. This is a topic that requires further investigation as it is questionable whether or not $\dot{V}O_{2max}$ is actually achieved in some test protocols.

To effectively answer the question regarding optimum training intensity, more longitudinal work will be needed. What appears to work best in the short-term may not be optimal over the long-term. Training is a complex process that must be studied over years, not just weeks and months. The interactions among intensity, duration and frequency are considerable, and the number of permutations possible for study is nearly endless. Detailed examination of periodisation will be required in answering this question.

The dominance of African runners in the last 2 decades may provide valuable insight into the training process. Their training appears to be relatively uncomplicated. In essence, intensity is emphasised over volume. African runners train at vigourous paces on a nearly daily basis and much of their running is done on hills. The frequency of the high intensity work results in a much higher percentage of their running mileage being at or above LT pace.[82] In contrast, in the author's opinion, training in western countries appears to be guided by a 'more is better' philosophy which necessitates limiting intensity. Furthermore, while elite athletes in most western countries can be physiologically assessed in the laboratory and training programmes modified accordingly, the success of such efforts is unknown. In international competition, however, African runners not having these advantages continue to predominate. One cannot help but wonder if some of the limitations inherent in scientific methodology (e.g. linear versus allometric scaling, reliance on laboratory data) also limit the quality of the feedback provided to athlete and coach. The fact that African runners 50 years ago were not competitive at world class levels and that they continue making progress in terms of setting new records suggests that genetic endowment is not the only cause for their success. In recent years, performance by American runners has declined, rather than improved, in spite of being exposed to more information about training, nutrition and hydration, etc. More extensive scientific examination of the training philosophy and techniques of African runners is needed, as well as testing these techniques in western runners.

3. Conclusion

Much knowledge has accumulated in recent decades about distance running performance and training. However, current research methodology is characterised by a number of flaws and assumptions that limit progress in our understanding. Further development and insight into distance running will require addressing, at minimum, the following methodological issues: more longitudinal work is needed, training status of participants should be described in detail, the state of rest, nourishment and hydration should be assessed and reported, allometric scaling should be used more frequently to express $\dot{V}O_2$ particularly when body mass is variable, anaerobic power and physical structure should be incorporated in studies aimed at predicting or explaining variance in performance, the role of the brain as a central governor needs to be further assessed in a variety of exercise intensities and environments and more data are needed in competitive and field conditions rather than relying on laboratory testing.

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References

1. Billat V. Interval training for performance: a scientific and empirical practice. Sports Med 2001; 31: 13-31
2. Jones A, Carter H. The effect of endurance training on parameters of aerobic fitness. Sports Med 2000; 29: 373-86
3. Joyner M. Physiological limiting factors and distance running: influence of gender and age on record performance. Exerc Sport Sci Rev 1993; 21: 120-61
4. Wenger H, Bell G. The interactions of intensity, frequency, and duration of exercise training in altering cardiorespiratory fitness. Sports Med 1986; 3: 346-56
5. Berg K, Latin R, Hendricks T. Physiological and physical performance changes in female runners during one year of training. Sports Med Train Rehab 1995; 5: 311-9
6. Kurz M, Berg K, Latin R, et al. The relationship of training methods in NCAA Division I cross-country runners and 10,000-meter performance. J Strength Cond Res 2000; 14: 196-210
7. Martin D, Vroon D, May D, et al. Physiological changes in elite male distance runners' training. Phys Sportsmed 1986; 14: 152-66
8. Nelson R, McGregor R. Biomechanics of distance running: a longitudinal study. Res Q 1976; 47: 417-28
9. Tanaka K, Matsuura Y, Matsuzaka A, et al. A longitudinal assessment of anaerobic threshold and distance running performance. Med Sci Sports Exerc 1984; 16: 278-82
10. Sawka M, Convertino V, Eichner E, et al. Blood volume: importance and adaptations to exercise training, environmental stresses, trauma/sickness. Med Sci Sports Exerc 2000; 32: 332-48
11. Tonkonogi M, Walsh B, Svensson M, et al. Mitochondrial function and antioxidative defense in human muscle: effects of endurance training and oxidative stress. J Physiol 2000; 528: 379-88
12. Hickson R, Hagberg J, Ehsani H, et al. Time course of the adaptive responses of aerobic power and heart rate to training. Med Sci Sports Exerc 1981; 13: 17-20
13. Rusko H. Development of aerobic power in relation to age and training in cross-country skiers. Med Sci Sports Exerc 1992; 24: 1040-7
14. Costill D. Inside running: basics of sports physiology. Indianapolis (IN): Benchmark Press, 1986: 178
15. Wilmore J, Costill D. Physiology of sport and exercise. 2nd ed. Champaign (IL): Human Kinetics, 1994: 194
16. Costill D. The 1985 CH McCloy research lecture: practical problems in exercise physiology research. Res Q Exerc Sport 1985; 56: 378-84
17. Zauner C, Maksud M, Melichna J. Physiological considerations in training young athletes. Sports Med 1989; 8: 15-31
18. Rusko H. The effects of training on aerobic power characteristics of young cross-country skiers. J Sports Sci 1987; 5: 273-86
19. Noakes T. The lore of running. Champaign (IL): Leisure Press, 1991: 30
20. Astrand PO, Rodahl K. Textbook of work physiology. New York: McGraw-Hill, 1986: 423-7
21. Scrimgeour A, Noakes T, Adams B, et al. The influence of weekly training distance on fractional utilization of maximum aerobic capacity in marathon and ultramarathon runners. Eur J Appl Physiol 1986; 55: 202-9
22. Sjodin B, Svendenhag J. Applied physiology of marathon running. Sports Med 1985; 2: 83-99
23. Acevedo E, Goldfarb A. Increased training intensity effects on plasma lactate, ventilation threshold and endurance. Med Sci Sports Exerc 1989; 21: 563-8
24. Christensen E, Hedman H, Saltin B. Intermittent and continuous running. Acta Physiol Scand 1960; 50: 269-86
25. Daniels J, Scardina N. Interval training and performance. Sports Med 1984; 1: 327-34
26. Fox E, Robinson S, Wiegman D. Intensity and distance of interval training programs and changes in aerobic power. Med Sci Sports Exerc 1969; 27: 174-8
27. Miksell K, Dudley G. Influence of intense endurance training on aerobic power of competitive distance runners. Med Sci Sports Exerc 1984; 16: 371-5
28. Costill D, Fox L. Energetics of marathon running. Med Sci Sports 1969; 1: 81-7
29. Costill D, Fink W. Plasma volume changes following exercise and thermal dehydration. J Appl Physiol 1974; 37: 521-5
30. Bergh U, Sjodin B, Forsberg A, et al. The relationship between body mass and oxygen uptake during running in humans. Med Sci Sports Exerc 1991; 23: 205-11
31. Daniels J, Daniels N. Running economy of elite male and elite female runners. Med Sci Sports Exerc 1992; 24: 483-9
32. Heil D. Body mass scaling of peak oxygen uptake in 20-to-79-yr-old adults. Med Sci Sports Exerc 1997; 29: 1602-8
33. Rogers D, Olson B, Wilmore J. Scaling for VO_2-to-body size relationship among children and adults. J Appl Physiol 1995; 79: 958-67
34. Coetzer P, Noakes T, Sanders B, et al. Superior fatigue resistance of elite, black South African distance runners. J Appl Physiol 1993; 75 (4): 1822-7
35. Weston A, Mbambo Z, Myburgh K. Running economy of African and Caucasian runners. Med Sci Sports Exerc 2000; 32: 1130-4
36. Bulbulian R, Wilcox A, Darabos B. Anaerobic contribution to distance running performance of trained cross-country athletes. Med Sci Sport Exerc 1986; 18: 107-13
37. Paavolainen L, Hakkinen K, Hamalainen I, et al. Explosive-strength training improves 5-km running time by improving running economy and muscle power. J Appl Physiol 1999; 86: 1527-33
38. Tharp L, Berg K, Latin R, et al. The relationship of aerobic and anaerobic power to distance running performance. Sports Med Training Rehab 1997; 7: 215-25
39. deGaray A, Levine L, Carter J. Genetic and anthropological studies of Olympic athletes. New York: Academic Press, 1974: 28-36
40. Sparling P, Wilson G, Pate R. Project overview and description of performance, training, physical characteristics in elite women distance runners. Int J Sports Med 1987; 8: 73-6
41. Wilmore J, Brown C, Davis J. Body physique and composition of the female distance runner. Ann N Y Acad Sci 1977; 301: 764-6
42. Berg K, Latin R, Coffey C. Relationship of somatotype and physical characteristics to distance running performance in middle age runners. J Sports Med Phys Fitness 1998; 38: 253-7

43. Noakes T. Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. Scand J Med Sci Sports 2000; 10: 123-45
44. Kayser B, Narici M, Binzoni T, et al. Fatigue and exhaustion in chronic hypobaric hypoxia: influence of exercising and muscle mass. J Appl Physiol 1994; 76: 634-40
45. Gibson A, Schabort E, Noakes T. Reduced neuromuscular activity and force generation during prolonged cycling. Am J Physiol Regul Integr Comp Physiol 2001; 281: R187-96
46. Foster C, Coye R, Crowe A, et al. Comparison of free range and graded exercise testing. Med Sci Sports Exerc 1997; 29: 1521-6
47. Foster C, Green M, Snyder A, et al. Physiological responses during simulated competition. Med Sci Sports Exerc 1993; 25: 877-82
48. Daniels J. Daniels' running formula. Champaign (IL): Human Kinetics, 1998: 97
49. Burfoot A. White men can't run. Runner's World 1992; Aug: 89-95
50. Dennis S, Noakes T. Advantages of a smaller body mass in humans when distance running in warm, humid conditions. Eur J Appl Physiol 1999; 79: 280-4
51. Marino F, Mbambo Z, Kortekaas E, et al. Advantages of smaller body mass in distance running in warm, humid environments. Pflugers Arch 2000; 441: 359-67
52. Nielsen B, Hales J, Strange S, et al. Human circulatory and thermoregulatory adaptation with heat acclimation and exercise in hot, dry environment. J Physiol 1993; 460: 467-85
53. Fuller A, Carter R, Mitchell D. Brain and abdominal temperatures at fatigue in rats exercising in the heat. J Appl Physiol 1998; 84: 877-83
54. Gonzales-Alonso J, Teller C, Andersen S, et al. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 1999; 86: 1032-9
55. Nybo L, Nielsen B. Perceived exertion is associated with an altered brain activity during exercise with progressive hyperthermia. J Appl Physiol 2001; 91: 2017-23
56. Morgan D, Daniels J. Relationship between VO_{2max} and the aerobic demand of running in elite distance runners. Int J Sports Med 1994; 15: 426-9
57. Pate R, Macera C, Bailey S, et al. Physiological, anthropometric, training correlates of running economy. Med Sci Sports Exerc 1995; 24: 1128-33
58. Anton-Kuchly B, Roger P, Varene P. Determinants of increased energy cost of submaximal exercise in obese subjects. J Appl Physiol 1984; 56: 18-23
59. Conley D, Krahenbuhl G. Running economy and distance running performance of highly trained athletes. Med Sci Sports 1980; 12: 357-60
60. Svendenhag J, Sjodin B. Physiological characteristics of elite male runners in and off-season. Can J Appl Sport Sci 1985; 10: 127-33
61. Myashita M, Miura M, Murase Y, et al. Running performance from the standpoint of aerobic power. In: Folinsbee L, Borgia J, Drinkwater B, et al., editors. Environmental stress: individual human adaptations. New York: Academic Press, 1978: 183-94
62. Horowitz J, Sidossis L, Coyle E. High efficiency of type 1 muscle fibers improves performance. Int J Sports Med 1994; 15: 152-7
63. Craib M, Mitchell V, Fields K, et al. The association between flexibility and running economy in sub-elite male distance runners. Med Sci Sport Exerc 1996; 28: 737-43
64. Gleim G, Stachenfeld N, Nicholas J. The influence of flexibility on the economy of walking and running. J Orthop Res 1990; 8: 814-23
65. Conley D, Krahenbuhl G, Burkett L, et al. Following Steve Scott: physiological changes accompanying training. Phys Sportsmed 1984; 12: 103-6
66. Jones A. A 5-year physiological case study of an Olympic runner. Br J Sports Med 1998; 32: 39-43
67. Franch J, Madsen K, Djurhuus M, et al. Improved running economy following intensified training correlates with reduced ventilatory demands. Med Sci Sport Exerc 1998; 30: 1250-6
68. Cavagna G. Storage and utilization of elastic energy in skeletal muscle. Exerc Sport Sci Rev 1977; 5: 89-129
69. Billat V, Flechet B, Petit B, et al. Interval training at VO_{2max} effects on aerobic performance and overtraining markers. Med Sci Sport Exerc 1999; 31: 156-63
70. Berg K, Sady S. Oxygen cost of running at submaximal speeds wearing shoe inserts. Res Q 1985; 56: 86-9
71. Hickson R, Dvorak B, Gorostiaga E, et al. Potential for strength and endurance training to amplify endurance performance. J Appl Physiol 1988; 65: 2285-90
72. Sharp R, Troup J, Costill D. Relationship between power and sprint freestyle swimming. Med Sci Sports Exerc 1982; 14: 53-6
73. Rundell K. Treadmill roller ski test predicts biathlon roller ski race results of top US biathlon women. Med Sci Sports Exerc 1995; 27: 1677-85
74. Sinett A, Berg K, Latin R, et al. The relationship between field tests of anaerobic power and 10-km run performance. J Strength Cond Res 2001; 15: 405-12
75. Schmidtbleicher D. Training for power events. In: Komi P, editor. Strength and power in sport. London: Blackwell Scientific, 1994: 381-95
76. Fitts R, Costill D, Gardetto P. Effect of swim exercise training on human muscle fiber function. J Appl Physiol 1989; 66: 465-75
77. Gaesser G, Wilson L. Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. Int J Sports Med 1988; 9: 417-21
78. Mader A. Evaluation of the endurance performance of marathon runners and theoretical analysis of test results. J Sports Med Phys Fitness 1991; 31: 1-19
79. Weltman A, Snead D, Seip R, et al. Percentages of maximal heart rate, heart rate reserve and VO_{2max} for determining endurance training in male runners. Int J Sports Med 1990; 11: 218-22
80. Hill D, Rowell A. Response to exercise at the velocity associated with VO_{2max}. Med Sci Sports Exerc 1991; 29: 113-6
81. DeMarie S, Koralsztein J, Billat V. Time limit and time at VO_{2max} during a continuous and an intermittent run. J Sports Med Phys Fitness 2000; 40: 96-102
82. Anderson O. Why are Kenyans best: Swedish scientist combs Kenyan runners' muscles for clues. Running Res News 1992; 8: 1-7

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