Biomechanical considerations for economical walking and running

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ABSTRACT

MARTIN, P. E. and D. W. MORGAN. Biomechanical considerations for economical walking and running. Med. Sci. Sports Exerc., Vol. 24, No. 4, pp. 467–474, 1992. It has been suggested that biomechanical factors play a role in explaining interindividual differences in movement economy, but it is not apparent how important this role is nor how consistently these factors explain such differences. The purpose of this review is to summarize our current state of knowledge regarding the relationships between gait economy and selected body structure and biomechanical factors. Because the research literature contains other review papers on this general topic, it is not the intent to provide a comprehensive analysis of all anatomical and biomechanical factors that have been examined previously. The review considers not only some topics of very recent interest (e.g., Does flexibility/joint range of motion affect gait economy? Can gait mechanics and economy be altered effectively via biomechanical feedback?), but also topics that have been examined considerably over many years (e.g., is economy of motion associated with body mass, mass distribution, speed of movement, stride length and rate, and gait kinetics?). Results from the many studies reviewed confirm the notion that several structural and biomechanical factors offer some potential for explaining economy differences between individuals. Nevertheless, the relationships that have been observed between economy and individual descriptors of body structure and gait mechanics have generally been weak and inconsistent from study to study. Variables that describe muscular effort appear to have the greatest potential for explaining metabolic energy demands during walking and running. Unfortunately, at present it is unclear what quantifiable descriptors can best reflect muscle force production.

ECONOMY, FLEXIBILITY, GAIT, MASS, MECHANICAL POWER, STRIDE LENGTH, STRIDE RATE

If one was to measure steady-state aerobic demand (i.e., economy) for a randomly generated sample of healthy adults for selected submaximal movement tasks, a considerable degree of intersubject variability would be observed. For example, Daniels et al. (13) reported aerobic demands for 13 competitive distance runners ranging from 33.2–43.0 ml·kg⁻¹·min⁻¹ for a 30-cm vertical stepping task, 39.5–45.1 ml·kg⁻¹·min⁻¹ for 1.78 m·s⁻¹ walking at 15% grade and 43.2–53.8 ml·kg⁻¹·min⁻¹ for 4.13 m·s⁻¹ running at 0% grade. They noted that individuals clearly were not either economical or uneconomical for all types of physical activity, suggesting that economy “is not a function of inherent muscular metabolic economy” (p. 613). As one potential explanation for these economy trends, they speculated that poor skill or faulty mechanics may contribute to economy differences between individuals. Fedak et al. (15) expressed the widely held assumption that most of the energy consumed during terrestrial locomotion can be attributed to energy consumption by muscles, and that “muscles use this energy while generating force and performing mechanical work” (p. 24). Williams and Cavanagh (69) identified a number of biomechanical variables that were significantly related to running economy, lending support to the hypothesis that running mechanics affect metabolic energy demand. The statements and results of these researchers clearly imply that biomechanical factors contribute significantly to the determination of economy of motion.

When reviewing the research literature, one can find many investigations in which the relationships between economy of motion and various physiological and environmental factors have been examined. There are fewer analyses, however, that have considered the relationships between economy and various body structure and biomechanical factors. Despite the belief that biomechanical factors help to explain economy differences between individuals, it is not fully apparent to what extent these differences can be attributed to biomechanics nor how consistently biomechanical variables explain these differences. The purpose of this paper is not to attempt a comprehensive review of the all biomechanical assessments of gait economy, but rather to focus on a few selected anatomical and biomechanical factors organized around a series of questions pertaining to the relationship between these factors and economy. The reader is referred to other published reviews and

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analyses (e.g., 6,69,73) for additional perspectives on the topic.

ARE SELECTED DESCRIPTORS OF BODY STRUCTURE RELATED TO WALKING AND RUNNING ECONOMY?

Body mass. Because walking and running are activities in which body mass is supported by the lower extremities and is alternatively accelerated and decelerated with each step, aerobic demand for both is typically normalized with respect to total body mass (e.g., ml·kg\(^{-1}\)·min\(^{-1}\)). The assumption implicit in this practice is that aerobic demand is independent of body mass once it has been normalized. Numerous studies can be found, however, that suggest this assumption is not justified when large variations in body mass exist. For example, it is generally well accepted in comparative zoology that large animals have a lower mass-specific cost of locomotion than small animals (e.g., 19,62,64). Based on data collected from 62 avian and mammalian species, Taylor et al. (62) formulated the following allometric equation relating aerobic demand to body mass and speed:

\[ \dot{V}O_2 = 0.533 \text{ M}_b^{0.316} \cdot \text{v}_s + 0.300 \text{ M}_b^{0.303} \]  

where \( \dot{V}O_2 \) is expressed in ml·kg\(^{-1}\)·s\(^{-1} \), \( \text{M}_b \) is body mass in kg, and \( \text{v}_s \) is velocity in m·s\(^{-1} \). They observed that mass-specific aerobic demand at an intermediate speed of locomotion varied by more than 1400% across animals ranging in body mass from 0.0072 to 254 kg (lower \( \dot{V}O_2 \) for larger animals), but that 90% of the predicted values from the allometric equation fell within 25% of the measured values.

While equation 1 may provide a reasonable first approximation of the aerobic demand of locomotion for a variety of animal species, the question remains as to whether the energetic cost of walking and running by adult humans with their more narrow range of body mass reflects the same mass-specific cost as the animal-based research noted previously. Work by Davies and Thompson (14) and Skinner et al. (58) showed no differences in mass-specific aerobic demand for adults of different body mass and for lean, obese, and weighted lean individuals, respectively. In contrast, Williams et al. (71) and Williams and Cavanagh (70) reported inverse relationships between body mass or weight and submaximal \( \dot{V}O_2 \) for elite female distance runners \( \text{r} = -0.52 \) and elite male runners \( \text{r} = -0.39 \), demonstrating that heavier individuals had lower mass-specific aerobic demands. For the elite male runners, they noted that anthropometric variables, rather than those describing running mechanics, correlated most highly with economy. In particular, those reflecting linear dimensions of the body (e.g., leg length, pelvic width, and foot length) showed the strongest links to economy with correlations ranging from \(-0.55 \) to \(-0.68 \).

In an extensive assessment of six groups of endurance athletes, Bergh et al. (1) found that higher body mass is associated with lower aerobic demand per kilogram of body mass. They suggested that it may be more appropriate to express \( \dot{V}O_2 \) as ml·min\(^{-1} \)·kg\(^{-0.75} \) rather than the more typical units of ml·min\(^{-1} \)·kg\(^{-1} \). The authors were quick to caution, however, that their results "are not a priori attributable to effects of body mass per se, since body mass may correlate with a number of other variables, e.g., body surface area and stride frequency, which may affect the energy demand of running" (p. 209). This latter point is consistent with comments by Taylor et al. (63). In noting that the cost of generating muscle force has been suggested to be proportional to the rate at which actin-myosin cross-bridges cycle (34), Taylor et al. speculated that smaller animals with higher movement cycle rates and thus higher intrinsic muscle velocities would reflect higher metabolic demands.

From the results of these studies, it seems reasonable to conclude that larger individuals are more economical per unit of body mass than smaller individuals. Researchers should exercise care when designing economy experiments and reporting walking and running economy results so that body mass does not become an important experimental confound.

Body mass distribution. Many functional morphologists have assumed that the energetic cost of locomotion is an important factor influencing the evolution of limb structure in terrestrial animals (e.g., 21,29,33). This argument is based on the notion that a major portion of metabolic demand during walking and running is associated with accelerating and decelerating the limbs with each stride. Thus, assuming all other factors (e.g., speed, total body mass, running style) are reasonably similar, an individual whose extremities present a smaller inertial load to the musculature for these accelerations should be more economical (65). Stated more explicitly, individuals who have less mass concentrated in the limbs and who have limb mass concentrated more proximally or closer to primary axes of rotation require less muscular effort to accelerate the limbs.

While this hypothesis is intuitively appealing and is based on fundamental mechanical principles, no direct support for the hypothesis has been provided, partly because of the difficulty associated with accurately estimating segment inertial properties in living animals. Taylor et al. (65) tested the hypothesis by comparing the aerobic demands during running of three species of animals (cheetah, goat, and gazelle) of approximately the same body mass and limb lengths, but quite different limb masses and mass distribution within the limbs. Despite considerable differences in limb configuration, particularly between the cheetah and the two remaining species, there was little difference in aerobic demand between species at several speeds of running. Taylor and colleagues suggested that either energy expenditure associated with limb acceleration represented a much
smaller proportion of total energy cost than originally thought or the cheetah's considerably larger limb moment of inertia was offset by greater elastic energy utilization. They concluded that the effect of differences in mass distribution on economy was too small to measure.

Support for the hypothesis that individuals are more economical when a smaller proportion of body mass is concentrated in the extremities generally comes from studies in which segment inertial properties have been modified artificially via addition of mass to segments (e.g., 4,10,28,37,40,48,52,59). In most studies, the added load is concentrated in a small area on a segment. While it cannot be assumed that mass concentrated in a specific location on a limb can effectively simulate normal segment mass distribution, artificial loading offers the experimental advantage of providing a controlled and calculable manipulation of a segment’s inertial properties. Results of these studies indicate that carrying load on the trunk demands less additional metabolic cost than carrying load on the extremities, particularly the legs. In addition, it is more economical to carry load on the proximal rather than distal aspects of the extremities. As an example, the percent increase in the absolute cost of running per kg of added mass is approximately 1% for mass added to the trunk, 3.5% for mass added to the thighs, and 7.0% for mass added to the feet (48,52). From these discussions it appears that the mass distribution hypothesis is theoretically sound and appealing, but it remains unclear whether normal variations in segment mass distribution are of sufficient magnitude to account for a significant portion of interindividual variability in walking and running aerobic demand.

Flexibility/joint range of motion. Aerobic demand of walking and running is known to be adversely affected by advancing age in adults (22,43,53,67) and by lower extremity orthopedic pathologies (e.g., 2,18,66,68). Similarly, musculoskeletal flexibility also tends to decline with age and joint pathologies. Thus, one can speculate that increased aerobic demand and reduced flexibility in these special populations are related. For example, flexibility declines could result in a modified gait pattern (e.g., shorter stride length) that is less economical or in increased muscular effort to produce the same gait pattern because of increased resistance to motion near the extremes of the range of motion. Unfortunately, little data are available considering the potential link between flexibility and economy for either special populations, such as the aged and diseased, or healthy young adults. In one of the few published studies on the topic, Gleim et al. (20) found that higher “nonpathological musculoskeletal tightness” based on 11 measures of trunk and lower extremity flexibility was related to lower aerobic demands during walking and jogging. At the least economical speed of 2.24 m·s⁻¹, their composite flexibility score (more flexible was reflected by a lower score) was inversely related to aerobic demand (r = −0.43). The authors speculated that elastic energy contributions may be enhanced and that the need for neutralization of unproductive movements by active musculature may be reduced in less flexible individuals, which in turn lowers the metabolic cost of producing the movement. Given the paucity of information available, there clearly is a need for additional research on the specific effects of flexibility and other structural features on the economy of motion.

ARE SELECTED DESCRIPTORS OF WALKING AND RUNNING KINEMATICS RELATED TO ECONOMY OF MOTION?

Speed. In many analyses of gait economy, aerobic demand comparisons between individuals or groups are made at a specific speed of walking or running with VO₂ expressed in ml·kg⁻¹·min⁻¹. Any confounding effect of speed is thereby eliminated. It is obvious that as speed increases the rates of oxygen consumption for both walking and running increase systematically. When oxygen consumption is expressed relative to distance traveled (ml·kg⁻¹·m⁻¹), however, differences in the speed-economy relationships between walking and running become apparent. Previous research clearly suggests there is a most economical speed of walking, but not one for running. A U-shaped speed-economy relationship is apparent for walking with a minimum aerobic demand to walk a given distance at approximately 1.3 m·s⁻¹ (8,36,53,56). Furthermore, preferred walking speed for individuals is generally quite close to the most economical speed. It must be noted, however, that increases in cost per unit distance are most apparent at low and high speeds of walking. For example, Ralston (56) reported that energy expenditure (cal·m⁻¹·kg⁻¹) was minimized at 1.23 m·s⁻¹ but that the speed energy expenditure curve was nearly flat between approximately 1.1 and 1.4 m·s⁻¹.

In contrast to walking, the energy cost to run a given distance is reasonably similar regardless of the speed. Research done since 1950 generally supports the concept of a linear relationship between running speed and aerobic demand (e.g., 11,42,45,46). Daniels (11) noted, however, that the “concept of a linear relationship between velocity and VO₂ seems to hold up during submaximal running, where energy demands are met aerobically and where the range of running speeds is rather limited” (p. 333). He found the slope of the speed-economy curve varied slightly depending upon the range of speeds chosen for analysis. At slow running speeds, slopes were lower or flatter than those when only higher speeds were examined (12).

Stride length/rate. The effect that stride length and rate have on gait economy during steady-state submaximal exercise lends itself to simple experimental assesse-
ment because of the deterministic relationship between stride length, stride rate, and velocity and our ability to control velocity via treadmill walking or running. The protocol used most frequently involves first determining the preferred stride length/rate combination at a particular velocity, followed by aerobic demand tests during which subjects match their stepping rate to some form of audio signal to produce desired deviations in stride length and rate from the preferred condition. Most of the research effort to date has been concentrated on describing the effect of stride length and rate changes on economy, while minimal effort has been directed toward establishing the mechanisms underlying the economy response and determining whether the mechanisms can be defined primarily as rate-based or length-based phenomena.

Numerous studies (7,9,26,31,41,51,55) have consistently demonstrated that the aerobic demand of walking or running at a controlled speed tends to increase curvilinearly as stride length is either lengthened or shortened (and thus, stride rate is either decreased or increased, respectively) from that which is the preferred condition of an individual, resulting in a U-shaped stride length/rate-economy response. While a small percentage of subjects have displayed preferred stride length/rate combinations that deviated substantially from that at which aerobic demand was minimized, the preferred and optimal stride length/rate combinations for most individuals have been in close agreement. In addition, results suggest that economy is not particularly sensitive to small deviations in stride length and rate near the optimal combination because the stride length/rate-economy curve is reasonably flat in this region. Only when stride length and the rate are varied considerably from the optimal combination is aerobic demand substantially increased.

The specific mechanisms underlying the U-shaped stride length/rate-economy response are unclear, but may be associated with fundamental muscle force and power generating capabilities. Hill (30) demonstrated that muscle efficiency varies with shortening velocity such that a most efficient velocity exists. Changes in stride length and rate require concomitant changes in the rates of muscle lengthening and shortening and rate of force development, which ultimately should affect aerobic demand (24,42,61,63). Kaneko et al. (39) expanded on this notion by considering the role that fiber recruitment might play in generating necessary muscle power and determining aerobic demand. They observed similar U-shaped relationships between economy and stride rate and between economy and total body mechanical power. At low stride rates, external mechanical power, computed from kinetic and potential energy changes of the body center of mass, was high. At high stride rates, the mechanical power associated with moving the limbs was at its highest level. They speculated that these extreme conditions require a greater reliance on less economical fast twitch fibers than more intermediate stride length/stride frequency combinations.

Holt et al. (32) considered the possibility that stride length/rate optimization, and thus minimization of aerobic demand, is directly associated with anthropometric and inertial characteristics of the legs. By modeling the leg as a force-driven harmonic oscillator, they were able to predict a resonant frequency at which the force necessary to maintain normal motion was minimized. Their results supported their hypothesis that “the resonant frequency of a harmonic oscillator can accurately predict the stride frequency chosen by subjects when appropriate adjustments are made to the formula based on an optimization criterion of minimum force” (p. 64). Thus, they concluded that “motor control parameters emerge from the physical attributes of the system” (p. 66) and that resonance is the manner in which muscular effort is minimized.

ARE SELECTED DESCRIPTORS OF WALKING AND RUNNING KINETICS RELATED TO ECONOMY OF MOTION?

Ground reaction forces. Because kinetic characteristics of gait mechanics provide more direct insight into how muscular forces generate and control movement of the body, it is reasonable to speculate that kinetic features may show a stronger association with the energy requirements of gait than kinematic descriptors. The ground reaction force (GRF) has been studied extensively by gait specialists partly because it reflects the net effect of muscular action and segment accelerations while the body is in contact with the ground. Surprisingly little attention, however, has been given to the potential link between GRF descriptors and gait economy. In comprehensive analyses of elite and recreational distance runners, Williams and Cavanagh (69,70) reported moderate to weak relationships between GRF characteristics and economy. For example, support time and peak medial force correlated positively with aerobic demand (r = 0.49 and 0.50, respectively), indicating that shorter support times and lower medial peak forces were associated with better economy. More economical runners reflected significantly lower first peaks in the vertical component of the ground reaction force and tended to have smaller antero-posterior and vertical peak forces and more of a rearfoot striking pattern. Williams and Cavanagh suggested that lower extremity kinematics just prior to ground contact and the need to provide cushioning during early contact may have an important effect on the demands placed on the muscles both before and during support, which in turn may affect economy. Those individuals who strike the ground more forward on the foot may have to rely more heavily on the
musculature to assist with cushioning than rearfoot strikers who perhaps can rely more on footwear and skeletal structures to cushion and support the contact force.

**Mechanical power.** The majority of biomechanical analyses of gait economy have examined the relationships between aerobic demand and rather specific descriptors of discreet events in the gait cycle. In general, these relationships have not been strong. Because aerobic demand can be viewed as a global descriptor of the physiological demand of walking or running, one can speculate that a global descriptor of muscular effort would be more closely associated with economy than descriptors of discreet instants or events of the gait pattern. Mechanical power output reflects one way of globally, but indirectly expressing muscular effort. Assuming that a substantial portion of the metabolic demands of walking and running is attributed to muscles doing work (i.e., actively shortening or lengthening), then mechanical power should be an effective predictor of gait economy. Despite a large volume of research that has quantified mechanical work and power for walking and running, only a limited number of analyses has specifically examined the potential of mechanical power descriptors to explain interindividual differences in gait economy.

Mechanical power for both individual subjects and groups of subjects has been shown to exhibit a strong positive relationship with walking or running speed (3,5,15–17,23,24,38,44,57) and aerobic demand when considered across a wide range of walking or running speeds (3,57). Both Burdett et al. (3) and Shorten et al. (57) computed multiple descriptors of mechanical power output and reported correlations between aerobic demand and mechanical power that exceeded 0.79 for walking and running. This is not surprising because both aerobic demand and mechanical power are speed dependent. Unfortunately, these analyses do not address the question as to whether mechanical power descriptors can explain interindividual differences in gait economy at a specific speed of locomotion.

Williams and Cavanagh (69) found several power-related descriptors to be significantly related in the expected directions to aerobic demand at a single speed of running for a group of recreational runners. Net positive power was one of three significant predictors of economy in a multiple linear regression model that accounted for 54% of the variation in aerobic demand. In addition, the least economical runners displayed significantly less (approximately 26%) mechanical energy transfer between the legs and the trunk than their more economical counterparts. While not statistically significant, more economical runners displayed lower net positive power, lower total mechanical power, and greater between segment energy transfer than the less economical runners.

In contrast, Taylor and colleagues (15,23,24,60–63) have concluded that mechanical work or power does not satisfactorily explain economy variations among species of animals varying widely in body size. In general, they observed that the mechanical work required to maintain locomotion speed and limb motion showed no relationship with metabolic demand, neither as a function of speed or animal size. Clearly a major limitation of mechanical power computations, is their inability to account for isometric contributions of muscles during gait. For example, considerable muscular effort is needed to support the weight of the body with each step, a function that would contribute little to measured mechanical work. Other limitations of the commonly used methods for computing mechanical power, which further limits their value for explaining metabolic demand, have been summarized in a comprehensive review of the subject by van Ingen Schenau and Cavanagh (35).

Recent research in our laboratory (27,47) has considered an alternative expression for muscular effort that can account at least partially for isometric actions. Total body angular impulse, computed by integrating the absolute values of net joint moments of force and summing across joints, correlated positively with aerobic demand ($r = 0.32$ and 0.42 for walking and running, respectively) as expected, but failed to explain a significantly greater portion of economy variance than several kinematic and kinetic-based expressions of mechanical power.

Taylor and colleagues (24,25,42,61,63) have provided evidence that the metabolic demand of walking and running is proportional to the force developed by the muscles, which is associated with the need to support the weight of the body, and the rate at which these forces are developed. Size differences in cost have been shown to be proportional to stride frequency (24,25), which suggested that the time available for developing force during each stride is an important determinant of cost (42). Kram and Taylor (42) subsequently hypothesized that the weight specific rate of energy expenditure during running is inversely proportional to the time a single foot applies force to the ground during each stride. Results for five species of animals ranging in body mass from 30 g to 140 kg confirmed their hypothesis from which they concluded that “the cost of running is primarily determined by the cost of supporting the weight and by the time course of force application” (p. 266).

**CAN WALKING AND RUNNING ECONOMY BE MODIFIED VIA BIOMECHANICAL FEEDBACK OR TRAINING?**

Based on the information that has been presented for kinematic and kinetic descriptors of gait, one may
conclude that the association between biomechanical descriptors of walking and running patterns and gait economy is complex and elusive. Nevertheless, a close examination of published data demonstrates that some individuals clearly do not display economical movement patterns. A particular runner, for example, may tend to significantly over- or understride. From an energy conserving standpoint, such individuals may clearly benefit from changes in their pattern of motion. Unfortunately, only a few researchers have attempted to consider whether lasting changes in gait mechanics that significantly affect economy can be produced through biomechanical training.

Results from four recent studies fail to reflect a consensus on the effects of biomechanical training on gait economy and technique. Petray and Krahnenbuhl (54) found that the running economy, stride length, and vertical displacement of 10-yr-old boys were not significantly improved by an 11-wk instruction program that consisted of 5 min of instruction per week on various aspects of running technique, including “reducing unnecessary vertical displacement, awareness of stride rate and length, and general suggestions regarding posture and relaxation” (p. 252). Messier and Cirillo (49) reported significant but generally modest changes in gait descriptors, but no significant changes in either oxygen consumption or rating of perceived exertion for female adult novice runners after 15 20-min treadmill training runs during which subjects received visual and verbal feedback on trunk inclination, arm swing, lower extremity mechanics, and vertical oscillation. Miller et al. (50) provided visual feedback for a single technique factor to four uneconomical runners during 10 20-min training sessions. These four subjects displayed reductions in aerobic demand greater than those observed in control subjects, but changes were not statistically significant. Finally, Williams et al. (72) evaluated the effect of training at a longer than optimal stride length on numerous running technique descriptors and aerobic demand. Post-training technique descriptors were generally intermediate to those of the pretraining and imposed training values, but most kinematic adaptations were not significant. Post-training aerobic demand was significantly less than pretraining values, a change opposite to that which would be expected. The VO₂ decline also was not specific to the training stride length but rather occurred across all tested stride length conditions.

SUMMARY

Four general questions have been raised throughout this review. Are selected descriptors of body structure related to walking and running economy? Are selected descriptors of walking and running kinematics related to economy of motion? Are selected descriptors of walking and running kinetics related to economy of motion? Can walking and running economy be modified via biomechanical feedback or training? While there are too little data available to answer the final question, the answer to the first three questions is a qualified “yes.” It has been shown that several structural and biomechanical factors offer some potential for explaining economy differences between individuals. Nevertheless, the relationships that have been observed between economy and individual descriptors of body structural and gait mechanics have generally been weak and inconsistent from study to study. Variables that describe muscle force production clearly have the greatest potential for explaining metabolic energy demands during walking and running, and therefore offer the potential to explain interindividual differences in economy. Unfortunately, at the present time we must rely on indirect indicators of muscular effort, and it is unclear which variables serve this role consistently and effectively.

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