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Research article

Influence of gait manipulation on running economy in female distance runners

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Abstract
The aim of this investigation was to determine if gait manipulation influences running economy. Following 30 minutes of accommodation to level treadmill running at 3.35 $m \cdot s^{-1}$ and determination of $\dot{V}O_{2peak}$, nine female distance runners (age = 23.3 ± 4.2 years; body mass = 57.5 ± 5.2 kg; height = 1.64 ± 0.10 m; body fat = 11.4 ± 2.4 %; $\dot{V}O_{2peak}$ = 54.9 ± 4.1 $ml \cdot kg^{-1} \cdot min^{-1}$) completed two treadmill running sessions. In each session, standing $\dot{V}O_2$ was measured and subjects ran for 6 minutes at 3.35 $m \cdot s^{-1}$ under 4 randomly-selected conditions: a) normal running (NL), b) hands behind back (BK), c) hands on head (HD), and d) running with exaggerated vertical oscillation (VOSC). During the last 2 minutes of each running bout, samples of expired air were analyzed to determine oxygen uptake ($\dot{V}O_2$). Data obtained by averaging gross $\dot{V}O_2$ values across sessions indicated that VOSC (51.0 ± 2.5 $ml \cdot kg^{-1} \cdot min^{-1}$) and HD (46.1 ± 2.0 $ml \cdot kg^{-1} \cdot min^{-1}$) resulted in significantly ($p < 0.05$) elevated $\dot{V}O_2$ values compared to BK (43.9 ± 2.4 $ml \cdot kg^{-1} \cdot min^{-1}$) and NL (43.4 ± 2.6 $ml \cdot kg^{-1} \cdot min^{-1}$). $\dot{V}O_2$ measured during VOSC was also higher compared to HD. Viewed in concert, these results suggest that specific gait manipulations can produce marked decrements in running economy among trained female distance runners.

Key words: Biomechanics, oxygen uptake, distance running, female runners.

Introduction

Running economy is defined as the steady-state aerobic demand ($\dot{V}O_2$) for a given velocity of walking or running (Daniels, 1985; Klein et al., 1997; Morgan et al., 1989; 1990; Saunders et al., 2004). In order to improve running economy, coaches may be tempted to manipulate certain aspects of an athlete's running motion (Slocum and Bowerman, 1962). While several investigations have demonstrated an association between running economy and a variety of kinematic and kinetic parameters (Cavanagh et al., 1977; Cavanagh and Williams, 1982; Frederick, 1985; Kyrolainen et al., 2001; Lake and Cavanagh, 1996; Williams and Cavanagh, 1987; Williams et al., 1987), limited research exists describing changes in running economy that result from direct manipulation of gait mechanics. In 1952, Högberg observed that as step length (SL) was systematically shortened and lengthened compared with freely-chosen step length (FCSL), $\dot{V}O_2$ increased in a curvilinear fashion in a single, well-trained subject. More recent findings have also revealed increases in $\dot{V}O_2$ of 7.1% and 4.7% as SL was lengthened and shortened by +8.0% and –8.0% of leg length (LL) from the FCSL, respectively. Results of this biofeedback manipulation study displayed a U-shaped response in $\dot{V}O_2$ among competitive racewalkers who racewalked at SLs at varying percentages of LL from their FCSL (Morgan and Martin, 1986). In another biofeedback (audio and visual) study, Morgan and colleagues (1994b) demonstrated that $\dot{V}O_2$ increased by 5.4%, 9.8%, and 12.6% as SL was lengthened +4.2%, +9.5%, and +12.2%, respectively, from the participants' FCSL. With respect to shortening, however, $\dot{V}O_2$ increased 3.2% as SL was shortened -19.8% from the particpants' FCSL (Morgan et al., 1994b). Taken together, these and other studies (e.g. Hreljac and Martin, 1993; Kaneko et al., 1987) demonstrate that energy demand increases in a U-shaped pattern when SL is either lengthened or shortened from the preferred SL.

While variations in SL can alter running economy, surprisingly little is known regarding the effects of other biomechanical manipulations on $\dot{V}O_2$. In a study published in abstract form, Egbuonu et al. (1990) reported that $\dot{V}O_2$ increased when trained female distance athletes ran with their hands behind their back or ran with an exaggerated vertical oscillatory pattern (i.e. greater bouncing motion). These authors noted, however, that the increase in $\dot{V}O_2$ (range = 4.0% to 4.6%) for such major alterations in running style was relatively small in magnitude. Based on these data, it was suggested that the direct link between running mechanics and running $\dot{V}O_2$ might not be particularly strong (Egbuonu et al., 1990).

Against this background data, the purpose of the present study was to further elucidate the question of whether alterations in running style produce changes in running economy among trained distance runners. In conducting this investigation, we sought to extend the results of Egbuonu and colleagues (1990) by carefully controlling the testing environment, examining the energetic impact of other biomechanical manipulations which have not been previously studied, and providing subjects with ample exposure to normal treadmill running and treadmill running at each gait manipulation.

Methods

Subjects

Nine female recreational distance runners (age = 23.3 ± 4.2 years; body mass = 57.5 ± 5.2 kg; height = 1.64 ± 0.10 m; body fat = 11.4 ± 2.4 %; $\dot{V}O_{2peak}$ = 54.9 ± 4.1

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ml·kg^{-1}·min^{-1}) with no orthopedic or cardiovascular limitations to exercise volunteered to participate in the present study. Prior to inclusion and subject testing, written informed consent, approved by the University Institutional Review Board, was secured from each participant. After height and body mass were measured, a Harpenden skinfold caliper (Baty International, England) was used to measure skinfold thickness at seven body sites (chest, triceps, midaxilla, subscapula, suprailium, abdomen, and thigh) in a serial fashion. A minimum of two complete sets of skinfold data were obtained on each participant in accordance with guidelines set forth by the American College of Sports Medicine (ACSM, 2007). If skinfold measurement at each body site varied by more than 1.0 mm, a third measure was taken and the two measures that were within 1.0 mm were averaged. The mean value for each skinfold site was summed and entered into sex-specific formulae to estimate body density (ACSM, 2007). Body fat percentages were then obtained by substituting body density values into both the Siri and Brozek equations (ACSM, 2007). The relative body fat percentages derived from the two equations were then averaged to derive a single percent body fat value for each participant.

The study protocol involved having each participant complete four testing sessions within a 2- to 3-week period. In an effort to minimize extraneous variation in $\dot{V}O_2$, participants were asked to wear the same shoes and clothing for each session. Circadian variation was also minimized as participants were scheduled at approximately the same time of day for each of the four running sessions. Furthermore, participants were asked to refrain from eating and consuming caffeine-containing beverages three hours prior to testing. Details of each testing session are presented in the following section.

Session 1: Treadmill accommodation

The primary goal of this session was to establish the presence of a stable metabolic response at the test velocity (3.35 m·s^{-1}) and to determine baseline vertical oscillation for each subject at this speed. To accomplish this, each participant completed five 6-min level (0% gradient) treadmill runs at 3.35 m·s^{-1}. This test velocity was deemed to be a comfortable pace that could be performed routinely by participants during their typical training runs (76.5% of $\dot{V}O_{2peak}$). A rest period of 5 to 10 min separated each running trial.

Prior to running, a reflective marker was placed on the superior border of the greater trochanter of the left leg (Cavanagh and Williams, 1982). For all trials, participants breathed through a mouthpiece that was connected to a low-resistance, breathing valve. Treadmill velocity was verified using a photoelectric cell mounted above the treadmill belt that recorded elapsed time for eight treadmill belt revolutions. This value was used, together with treadmill belt length, to set treadmill velocity at the desired value during the first minutes of running. Expired air was collected in a meteorological balloon during the last two minutes of each trial and analyzed to determine $\dot{V}O_2$. Samples of expired air were passed through a drying tube and analyzed using an Applied Electrochemistry Ametek S-3A/I oxygen analyzer and a CD-3A carbon dioxide analyzer (AEI Technologies, Pittsburgh, PA, USA) calibrated previously against primary gas standards of known concentrations (16.00% O_2 and 4.00% CO_2). A Rayfield gas meter (Rayfield Equipment Ltd., Waitsfield, VT, USA) calibrated against a Collins 120-L Tissot (Warren E. Collins, Braintree, MA, USA) was used to quantify expired gas volumes. During the final 60 seconds of each trial, each subject's running gait was filmed with a video recorder located approximately 11 meters away from the motorized treadmill and positioned perpendicularly to the plane of motion. Vertical oscillation of the hip marker for each runner was digitized over a range of 20 to 25 successive strides using the Peak Motus Measurement System (Revere Parkway, CO, USA). These values were averaged to derive mean vertical oscillation and standard deviation (SD) for each trial. Vertical oscillation data obtained from the five runs were subsequently averaged to calculate baseline (mean ± SD) vertical oscillation for each subject.

Session 2: Determination of peak aerobic power ($\dot{V}O_{2peak}$)

The aim of the second testing session was to determine $\dot{V}O_{2peak}$ in each runner. After an individually-determined warm up, participants began running at a velocity of 3.35 m·s^{-1} and at 0% grade. Following the first two minutes of running, treadmill velocity was increased to 3.57 m·s^{-1}, where it remained constant for the duration of the test. At 2-min intervals, treadmill grade was increased by 2.5% until volitional exhaustion. During the test, heart rate was determined from an electrocardiographic tracing. Expired air samples were collected in meteorological balloons at 1-min intervals toward the latter part of the test. Once participants indicated via hand signals that they were within one minute of finishing the test, a final 30- to 60-second expired air collection was obtained. $\dot{V}O_{2peak}$ was taken as the highest $\dot{V}O_2$ value obtained during the course of the test.

Sessions 3 and 4: Gait manipulation

The objective of the third and fourth testing sessions was to directly perturb the running technique of each participant and measure any change in $\dot{V}O_2$. Two separate testing days for each experimental session, spaced approximately 1 week apart, were allotted to determine day-to-day $\dot{V}O_2$ reliability of specific biomechanical manipulations.

At the beginning of each session, participants stood on the treadmill for 10 min and a sample of expired air was collected from minutes 5 to 10 in order to measure standing $\dot{V}O_2$. Once standing $\dot{V}O_2$ was determined, each participant ran for six minutes at 3.35 m·s^{-1} and at 0% gradient under four randomly assigned conditions. In the first condition, participants ran normally (NL). A second condition required participants to run with clasped hands placed behind the lower-lumbar, upper-sacral region of the back (BK). In the third condition, participants ran with clasped hands on top of the head (HD). Lastly, a fourth condition involved having participants run with an exaggerated vertical oscillatory motion (VOSC) that required them to lightly touch a foam pad with the top of the head. For each runner, this pad was located a distance equivalent to the baseline vertical oscillation value measured in Session 1 plus four times the SD of this value.

In the VOSC trial, as well as during the other gait conditions (NL, BK, HD), the amount of vertical oscillation was ascertained by digitizing the vertical oscillation of the hip marker during the last minute of running. For each gait condition, expired air samples were collected in meteorological balloons during the last two minutes of running and analyzed to determine gross $\dot{V}O_2$.

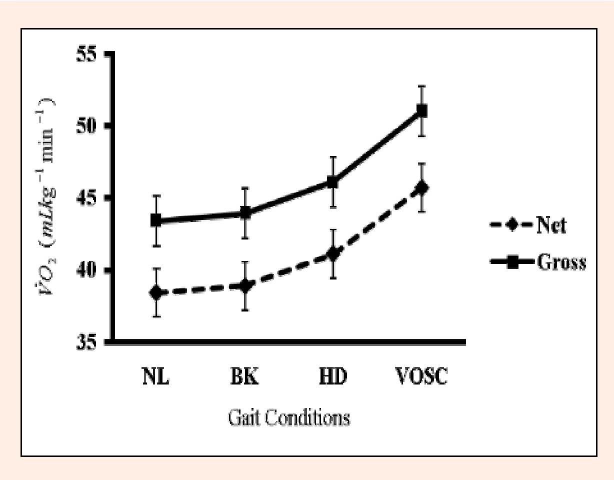

Figure 1. Average gross and net $\dot{V}O_2$ for the four running conditions. NL = Normal; BK = Hands Clasped Behind Back; HD = Hands Clasped on Top of Head; VOSC = Exaggerated Vertical Oscillation.

Statistical analyses

Descriptive statistics (mean ± SD) were computed to describe the subject population. The stability of $\dot{V}O_2$ measures obtained in Session 1 was assessed by performing repeated-measures analysis of variance (ANOVA) and calculating coefficient of variation (CV) and intraclass correlation coefficient values across the five 6-min treadmill running accommodation trials. For Sessions 3 and 4, gross $\dot{V}O_2$ values obtained during each running condition were compared using paired Student's t-tests. For each running condition, the reliability of submaximal gross $\dot{V}O_2$ data obtained between Sessions 3 and 4 was determined by calculating CV and intraclass correlation coefficient values. Findings from paired t-test analyses revealed no between-session differences in gross $\dot{V}O_2$ for each gait treatment. Average between-session CV values ranged from 0.4% to 2.9% for each running condition, while the mean intraclass correlation coefficient value for gross $\dot{V}O_2$ was 0.88. Net $\dot{V}O_2$ was calculated by subtracting standing $\dot{V}O_2$ from gross (exercise) $\dot{V}O_2$. The rationale for calculating net $\dot{V}O_2$ was to quantify the aerobic demand of running after accounting for the energy demands of standing. Paired t-test analyses revealed no between-session differences in net $\dot{V}O_2$ for each running condition. The average between-session CV values for net $\dot{V}O_2$ ranged from 1.3% to 2.4% for each gait condition, while the mean intraclass correlation coefficient value for net $\dot{V}O_2$ was 0.83. In addition, as displayed in Figure 1, the mean $\dot{V}O_2$ response for net $\dot{V}O_2$ across the four biomechanical conditions was similar to that observed for gross $\dot{V}O_2$. Given the similarity in, and stability of, gross and net $\dot{V}O_2$ responses across each gait manipulation, subsequent data analyses were performed on gross $\dot{V}O_2$ values for each running condition.

Overall differences in mean gross $\dot{V}O_2$ values for the four running conditions were analyzed using repeated-measures ANOVA. The Tukey Honestly Significant Difference (HSD) *post-hoc* procedure was used to specify the location of gross $\dot{V}O_2$ differences among treatment conditions. For all analyses, statistical significance was established at $p \leq 0.05$.

Results

Analysis of data collected in Session 1 revealed that participants displayed a stable metabolic response prior to gait manipulation. This was confirmed by the absence of differences in gross $\dot{V}O_2$ across running trials (Trial 1 $\dot{V}O_2$ = 43.1± 1.8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$; Trial 2 $\dot{V}O_2$ = 42.3 ± 1.9 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$; Trial 3 $\dot{V}O_2$ = 42.8 ± 1.5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$; Trial 4 $\dot{V}O_2$ = 42.8 ± 1.9 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$; Trial 5 $\dot{V}O_2$ = 43.3 ± 1.8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) and the presence of overall CV and intraclass correlation coefficient values for gross $\dot{V}O_2$ of 4.6% and 0.99, respectively.

Results from the repeated measures ANOVA and Tukey HSD test indicated that gross $\dot{V}O_2$ values for VOSC (51.0 ± 2.5 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) and HD (46.1 ± 2.0 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) were higher compared to values observed for BK (43.9 ± 2.4 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) and NL (43.4 ± 2.6 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$). Additionally, gross $\dot{V}O_2$ measured during VOSC was higher compared to HD. No significant difference in gross $\dot{V}O_2$ was detected between BK and NL.

Discussion

As described earlier, the mean $\dot{V}O_{2peak}$ (54.9 ± 4.1 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) of our participants reflected a good level of aerobic fitness. The range of daily variability in gross $\dot{V}O_2$ observed across the four running conditions is comparable to between-day CV values for $\dot{V}O_2$ (1% to 3%) reported among trained adult distance runners engaged in low-to-moderate intensity treadmill running (Morgan et al., 1991; 1994a; 1995; Pereira and Freedson, 1997; Saunders et al., 2004; Williams et al., 1991). Additionally, the average intraclass correlation coefficient for gross $\dot{V}O_2$ calculated from repeated tests performed for each manipulation (0.88) confirmed that subjects displayed relatively consistent daily $\dot{V}O_2$ responses. Viewed collectively, these data indicate that an acceptable level of day-to-day stability in gross $\dot{V}O_2$ was achieved across treatment conditions and provide support for our decision to average daily gross $\dot{V}O_2$ values obtained for each gait (manipulation) condition.

Data from the current study suggest that running economy can be noticeably worsened in female distance runners who adopt a gait style that deviates substantially from their normal running pattern. Relative to NL, a small, non-significant increase (1.3%) in mean gross $\dot{V}O_2$ was observed when participants ran with their hands behind their back. In contrast, average gross $\dot{V}O_2$ increased by 7% and 19% under HD and VOSC, respectively. These results differ from those of Egbuonu and associates (1990), who reported mean $\dot{V}O_2$ increases of 4.0% and 4.6%, respectively, when trained female distance runners ran with both hands behind their back or ran with an exaggerated bouncing motion. The larger increase in gross $\dot{V}O_2$ observed during VOSC may be related to the slightly higher vertical oscillation target employed in the current study (VOSC + 4 SD) compared to the target used by Egbuonu et al. (1990) (VOSC + 3 SD). All of the runners displayed a high degree of sensitivity to the VOSC and a wide spectrum of individual responses was noted (range of $\dot{V}O_2$ increase = 8.5% to 35.6%). Interestingly, the smallest relative individual increase in gross $\dot{V}O_2$ detected under the VOSC (8.5%) was nearly double the mean percentage rise in $\dot{V}O_2$ reported by Egbuonu and colleagues (1990) (4.6%) for the same gait manipulation condition.

In the present investigation, almost no change in gross $\dot{V}O_2$ above control values occurred when participants ran with both hands behind the back. With respect to this finding, vertical oscillation while running under the BK condition (8.7 cm) was nearly identical to the value measured during NL (8.9 cm). This similarity in vertical oscillation values may partly explain the lack of a significant difference in gross $\dot{V}O_2$ between these two conditions. In considering HD, vertical oscillation (9.5 cm) was 7% higher than the value measured for NL. This greater rise in vertical oscillation may have contributed to the increase in gross $\dot{V}O_2$ recorded during HD. Additionally, because placing the hands on top of the head raises the location of the body centre of mass, more muscle activity may have been required to maintain and stabilize balance while running, which would also lead to a rise in gross $\dot{V}O_2$.

As pointed out earlier, little empirical research has been conducted to directly substantiate or invalidate the association between running mechanics and running economy. In one of the few comprehensive studies examining this issue, Williams and Cavanagh (1987) determined that a number of biomechanical variables (e.g., net positive power, shank, trunk, and maximal plantar flexion angles, maximal knee flexion during support phase, minimum knee velocity, wrist and vertical oscillation) differentiated among groups of runners with elevated, average, or lower submaximal $\dot{V}O_2$ values. From a mechanistic perspective, the adoption of a particular gait pattern may influence $\dot{V}O_2$ by altering approach kinematics prior to ground contact, increasing lower extremity muscle activity and levels of muscle coactivation, producing higher levels of internal and external mechanical power, changing muscle fibre recruitment patterns, or disrupting the normal resonant frequency of lower limb oscillation (Holt et al., 1990; Kaneko et al., 1987; Martin and Morgan, 1992; Williams, 1990; Williams and Cavanagh, 1987).

It is reasonable to question the practical application of our findings because it is unlikely that runners would adopt such unnatural gait patterns under normal circumstances. Nonetheless, the magnitude of increases in gross $\dot{V}O_2$ reported for VOSC and HD raises the intriguing possibility that meaningful improvements in running economy might be achieved by manipulating the gait of distance runners who exhibit specific aspects of running style that deviate markedly from typical values. Relative to this point, some elite and well-trained runners display rates of submaximal $\dot{V}O_2$ that equal or exceed those measured in untrained subjects (Morgan et al., 1995). Hence, it is conceivable that runners who demonstrate relatively poor running economy might benefit from exposure to training programmes featuring the modification of specific running mechanics. While outcomes of studies featuring biomechanical feedback or endurance training have generally not been positive (Lake and Cavanagh, 1996; Messier and Cirillo, 1989; Miller et al., 1990; Petray and Krahenbuhl, 1985), Morgan and associates (1994b) reported that a 3-week period of audio-visual feedback training shifted the freely-chosen step length (FCSL) to a more optimal location on the SL- $\dot{V}O_2$ curve and reduced $\dot{V}O_2$ by nearly 4% in recreational distance runners displaying uneconomical FCSL patterns. Although this small relative decrease in submaximal aerobic demand might be viewed as trivial, it has been estimated that a 4% improvement in running economy would translate into an average savings of over three minutes in marathon performance (Morgan et al., 1994b). For the well-trained or elite runner, this level of performance improvement could markedly alter finish order in a long-distance race.

Conclusion

In conclusion, results from this investigation demonstrate that specific gait manipulations can produce substantial increases in oxygen uptake ($\dot{V}O_2$) during submaximal running in female distance runners. Although speculative, the magnitude of economy changes observed for some gait conditions suggest that modifications of biomechanical features among runners displaying uneconomical gait patterns might potentially lead to a dual improvement in running economy and distance-running performance.

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Key points

- This investigation demonstrates that specific biomechanical manipulations can produce substantive increases in the oxygen cost ($\dot{V}O_2$) of submaximal running in female distance runners.
- The magnitude of increases in $\dot{V}O_2$ reported in this study raises the intriguing possibility that meaningful improvements in running economy might be achieved by manipulating the gait of distance runners who exhibit specific aspects of running style that deviate markedly from the optimum.

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