

© Williams & Wilkins 1996. All Rights Reserved. Volume 28(6), June 1996, pp 737-743 The association between flexibility and running economy in sub-elite male distance runners [Applied Sciences: Biodynamics]
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ABSTRACT[^]

The purpose of this study was to examine the association between nine measures of limb and trunk flexibility and running economy. Within a week prior to running economy assessment, and after 10 min of jogging at $3.13 \text{ m}\cdot\text{s}^{-1}$, 19 well-trained male sub-elite distance runners underwent two complete sets of lower limb and trunk flexibility assessments. Runners then completed two 10-min running economy assessment sessions on consecutive days at $4.13 \text{ m}\cdot\text{s}^{-1}$ following two 30-min sessions of treadmill accommodation at $4.13 \text{ m}\cdot\text{s}^{-1}$. Intraclass correlation coefficients indicated that the repeated flexibility measurements were highly reliable ($\overline{R} = 0.92 \pm 0.09$), as were the two running economy appraisals ($R = 0.99$). Correlational analyses revealed that dorsiflexion ($r = 0.65$) and standing hip rotation ($r = 0.53$) were significantly ($P \leq 0.05$) associated with the mean aerobic demand of running, such that runners who less flexible on these measures were more economical. Although speculative, these results suggest that inflexibility in certain areas of the musculoskeletal system may enhance running economy in sub-elite male runners by increasing storage and return of elastic energy and minimizing the need for muscle-stabilizing activity.

It is well established that a high maximal ability to metabolize energy aerobically ($\dot{V}O_{2\text{max}}$) is a prerequisite for success in endurance running events (9,22,29). Once an athlete acquires this capacity, other factors can become decisive in determining performance (8). One such factor is submaximal aerobic demand at a given running velocity, otherwise known as running economy, which can vary among runners by as much as 30% (12). Studies have shown that differences in submaximal energy expenditure endow economical runners with an advantage over noneconomical runners of equal aerobic fitness, since they can run at faster velocities at standard percentages of $\dot{V}O_{2\text{max}}$ (8,10). Despite a growing body of literature on the subject of economy, factors responsible for variations in aerobic demand between runners remain to be established (27).

Findings from recent research efforts suggest that trunk and lower limb flexibility may affect running economy (20,21). In work by Godges and coworkers (21), running economy was

measured in seven moderately athletic male college students at 40%, 60%, and 80% of $\dot{V}O_{2\max}$ immediately before and after administration of static stretches designed to increase hip flexibility. They reported a reduced aerobic demand of running at all speeds when hip flexion and extension were increased. Improved hip flexibility, myofascial balance, and pelvic symmetry due to stretching were thought to enhance neuromuscular balance and contraction, thus leading to a lower submaximal $\dot{V}O_2$. Their results are compatible with general beliefs that improved flexibility is desirable for optimal running performance.

In contrast, Gleim and associates (20) tested 100 male and female subjects over a range of speeds from 0.9 to 3.13 $\text{m}\cdot\text{s}^{-1}$ and found that those who exhibited less flexibility in a battery of 11 trunk and lower limb flexibility tests were most economical. Possible explanations for this phenomenon are as follows.

Inflexibility in the transverse and frontal planes of the trunk and hip regions of the body may stabilize the pelvis at the time of foot impact with the ground, reducing excessive range of motion and metabolically expensive stabilizing muscular activity (20). Gleim and coworkers (20) have also suggested that elastic energy storage and return may be increased with a tighter musculotendinous system. Evidence to support this argument can be found in physiological literature. Ker (23) and Ker and associates (24,25) have demonstrated that tendon tissue stores and returns significant of elastic energy, and Asmussen and Bonde-Petersen (1) hypothesize that muscle can function in a similar fashion. Investigations conducted by Dawson and Taylor (15), Asmussen and Bonde-Petersen (1), and Ker (23) have all produced results showing that the elastic properties of tissue are enhanced if these tissues are stiff. Such findings suggest that tightness in the muscles and tendons could increase elastic energy storage and return and, therefore, lead to a reduced submaximal $\dot{V}O_2$ demand. In synopsis, there are plausible explanations for the surprising findings of Gleim and associates (20), which contradict previous results and current beliefs that improved flexibility is always desirable for optimal running performance.

It should be noted that the equivocal findings reported in the aforementioned flexibility and economy studies may be related, in part, to limitations in the methodological designs employed. Neither study (20,21), for instance, provided subjects with adequate treadmill accommodation (5,30), which, in the research design utilized by Godges and associates (21), may have resulted in an apparent improvement in running economy. Additionally, participants in both studies were not described as endurance athletes or well-trained runners. Such a lack of familiarity with running as a typical gait pattern may have made valid measurement of running economy unlikely. Lastly, in the study conducted by Gleim and coworkers (20), male and female subjects were combined in the analyses. Although these researchers reported no statistical differences in running economy between genders, they did state that females as a group were more flexible than males. Since women are generally less economical than men (4,11,13) and more flexible than men (2,6,7), the true association between flexibility and running economy may not be evident unless genders are studied separately. To summarize, because substantial support for either a positive or negative association between flexibility and running economy cannot be gleaned from these investigations, further study of the possible relationship between these two parameters is needed.

In view of the preceding discussion, the purpose of the present study was to examine the relationship between running economy and selected measures of trunk and lower limb flexibility by using methods that avoided the confounding factors noted in previous studies (20,21). It was theorized that selection of well-trained distance runners of a single gender, properly accommodated to treadmill running, would allow for a more focused examination of the association between the running economy and flexibility.

METHODS[^]

Subjects[^]

Nineteen locally competitive male distance runners participated in the study after giving written informed consent. Descriptive characteristics of the subjects are shown in Table 1. All subjects were engaged in a systematic running program at the time of the study and had finished a 10-km race in less than 40 min within the previous 12 months.

TABLE 1. Descriptive characteristics of the subjects.

After completing medical and health history forms, each runner participated in six testing sessions spaced over a 2-wk period. These sessions involved determination of $\dot{V}O_{2\max}$ (Session 1), assessment of trunk and lower limb flexibility (Session 2), accommodation to treadmill running (Sessions 3 and 4), and measurement of running economy (Sessions 5 and 6). To avoid possible effects of fatigue on lower body flexibility and running economy, runners refrained from racing and hard workouts during the study. The following section describes each testing session.

Session 1: Determination of $\dot{V}O_{2\max}$ [^]

To ensure that participants performed the economy runs at an aerobic effort, $\dot{V}O_{2\max}$ was assessed. Following a 3-min warm-up at $3.57 \text{ m}\cdot\text{s}^{-1}$ and 0% grade, treadmill speed was increased to $3.83 \text{ m}\cdot\text{s}^{-1}$ and remained constant for the duration of the test. At 2-min intervals, treadmill grade was increased by 2.5% until subjects reached volitional exhaustion. Expired gas samples were collected in meteorological balloons at 1-min intervals during the latter test stages and the contents were analyzed with Ametek O₂ (S-3A/1) and CO₂ (CD-3A) gas analyzers. The analyzers were calibrated at the beginning of each test using primary standard calibration gases. Expired ventilation was determined by evaluating the balloon contents through a calibrated Rayfield dry gas meter. $\dot{V}O_{2\max}$ was taken as the highest 1-min oxygen uptake value obtained in the test.

Session 2: Flexibility Assessment[^]

Approximately 2 d following the $\dot{V}O_{2\max}$ test, nine measures of trunk and lower limb flexibility were obtained over a 1-h period from each subject (see Fig. 1). This session occurred separately from the running economy assessment sessions due to the time-consuming nature of the

measurements and concern regarding the availability of subjects for long time blocks. Specific flexibility measures were selected because their assessment was thought to be reliably determined and indicative of flexibility in areas of the body (trunk, lower back, hips, buttocks, hamstrings, quadriceps, and calves) directly involved with distance-running flexibility. All flexibility measurements were made by the primary investigator, who had been trained by a local sports medicine physician and physical therapist. Measurements were made using a standard steel goniometer, a sit-and-reach board, and a GPM Swiss-made anthropometric kit.

Figure 1-Trunk rotation; quadriceps stretch; side bend.

Stretching was prohibited prior to commencing flexibility measurements so as to avoid individual variability in application of standardized or personal stretching regimes. Instead, all participants were similarly prepared for flexibility assessment by completing a 10-min warm-up period of treadmill running at $3.13 \text{ m}\cdot\text{s}^{-1}$. Following this, two complete sets of flexibility measurements were made on each runner. The second set of measurements was made blind to the first data set to remove investigator bias. When both sets of measurements were complete, the data were reviewed, and if any apparently different values were noted, an additional measurement was taken. The two closest measures of the three were averaged and used for statistical analysis. In cases where duplicate assessments of each measure were made on opposite limbs or for opposite trunk motions, all four values were averaged. Specific flexibility assessment procedures were conducted as follows (Figs.):

Figure 2-Standing external rotation of the hip; sit-and-reach; knee-to-chest.

Figure 3-Straight leg raise; dorsiflexion and plantarflexion.

Trunk rotation. Runners were seated with their pelvises firmly located against the rear of a chair. A wooden bar was then placed horizontally on their backs, along the shoulders just above the scapula. The hands of the runners grasped the bar approximately 30 cm from each shoulder to hold it in place and parallel with the line of the shoulders. While the runners' knees were held firmly by an assistant, thereby ensuring an unmoving pelvis, the trunk was rotated actively to the right and left as far as possible. At the point of greatest rotation in either direction, a goniometer measurement was made of the angular difference between the chair back (parallel with the pelvis) and the line of the bar along the shoulders.

Side bend. Standing straight, with feet together, runners were asked to reach as far as possible with both hands down the lateral sides of their thighs. Ink marks were made on each thigh at the furthest point reached by the fingertips. While keeping the feet together and the body aligned in the frontal plane, subjects were asked to lean to the right and left as far as possible, and ink marks were made at the furthest point reached by the fingertips down the side of the leg. The distance between the first and second mark on each leg was used to develop a ratio between side-bend length and total body height. This ratio was then used to compare side-bend trunk flexibility among runners.

Heel-to-buttocks (quadriceps stretch). Shoes were removed for this test. Runners stood with one leg on the floor and the other leg bent at the knee while the foot of the bent leg was pulled toward the buttocks. No goniometer measurement was made of this flexibility test. If participants were able to touch their buttocks with their heels, data sheets were checked yes on this variable. If they could not accomplish this task, their data sheets were checked no.

Standing external rotation of the hip with hip flexion at 90°. Runners were marked along their quadriceps with lines that connected the heads of the greater trochanters and the middle of the kneecaps. Once these lines were drawn, runners stood with their backs and pelvises firmly against a wall. Directly beneath the runners and perpendicular to the wall, a line was drawn. While the pelvis was held steady by an assistant, and while the runners grasped handles on the wall for stability, the knee was lifted so that the thigh reached a position parallel to the floor surface and parallel to the line drawn on the floor. The runners then actively bent the leg sideways toward the wall as far as possible, while keeping the thigh parallel with the floor. By looking down from above the line on the quadriceps and the line on the floor, outward hip rotation was measured with a goniometer.

Sit-and-reach. Runners were seated on the floor, legs stretched out before them and feet together against a sit-and-reach box. Without bending their knees and while keeping their hands even with each other, runners reached toward their toes (the zero mark) and beyond as far as possible. After four trials (each held statically for more than 2 s), the furthest point reached with their fingertips was taken as the sit-and-reach measurement.

Hip flexion. Runners lay stretched out upon their backs on a nonpadded table. The leg was bent at the knee and then drawn slowly and forcefully to the chest while the other leg was held straight on the table. The object of this test was to determine if right and left hip flexibility allowed for knee contact with the chest. If knee-to-chest contact occurred, the data sheet was checked yes on this measure. If knee-to-chest contact did not occur, the data sheet was checked no.

Straight leg raise. Runners lay stretched out upon their backs on a nonpadded table. A straight line was drawn from midknee through the greater trochanter to a midpoint on each side of the chest. While one leg was held flat on the table, the other leg was lifted straight up toward the ceiling and the head by an assistant. Care was taken to avoid external rotation of the leg and to keep the knee locked. The foot remained neutral during the procedure. Runners determined the degree of leg elevation by informing the primary investigator when excessive discomfort was experienced. The goniometer arms were then aligned with the straight portions of the now-bent

line on the thigh and chest, allowing for determination of hip flexion angle. In this measurement procedure, the smaller the goniometer angle, the larger the degree of straight leg bend.

Dorsiflexion of the foot. Runners lay stretched out upon their backs, knees locked, on a nonpadded table. Two lines were drawn on each lower limb, one on the lateral portion of each foot parallel with the plane of the sole, and the other between the bony prominences of the head of the fibula and the lateral malleolus. The goniometer arms were placed on these lines to measure the change in angle from 90° as the ball of the foot was pushed toward the trunk. The degree of passive stretch was set by the runners, who indicated when the stretch was maximal due to physiological limitation(s) or discomfort.

Plantarflexion of the foot. Runners lay stretched out upon their backs, knees locked, on a nonpadded table. Using the same lines drawn for dorsiflexion measurement, the goniometer was used to measure the change in angle from 90° as the top of the foot was pushed down and pointed away from the trunk. Again, the degree of passive stretch was set by the runners, who indicated when the stretch was maximal due to physiological limitation(s) or discomfort.

Sessions 3 and 4: Treadmill Accommodation[^]

Within a week of the $\dot{V}O_{2\max}$ test, subjects underwent treadmill accommodation to establish a stable gait pattern prior to assessment of running economy. The accommodation phase consisted of two running sessions performed on separate days. Each session consisted of three 10-min running trials at 4.13 m·s⁻¹, the first of which was preceded by a 4-min warm-up at 3.13 m·s⁻¹. Morgan and colleagues (28) have found that 30-60 min of treadmill accommodation appears to achieve stable running mechanics. Trials were separated by 10 min of rest in order to minimize fatigue effects. Treadmill velocity was determined from treadmill belt length and photocell determination of the elapsed time for eight treadmill belt revolutions.

Sessions 5 and 6: Running Economy[^]

Running economy assessments were made on two successive days, 1-2 d after the accommodation runs. Each running economy session consisted of a 5-min warm-up at 3.13 m·s⁻¹, followed by a 10-min run at 4.13 m·s⁻¹. During minutes 8-10 of each economy run, a 2-min expired gas sample was obtained for gas analysis. Procedures used for gas analysis were identical to those described for the $\dot{V}O_{2\max}$ test. The two economy sample values for each runner were averaged for descriptive purposes and correlational analyses. To minimize variability in economy due to circadian variation and shoe mass, each run was performed at the same time of day and in the same pair of shoes (27).

Statistics[^]

Paired two-tailed t-tests were used to assess differences in repeated measures of running economy and trunk and lower limb flexibility. Intraclass correlation coefficients were subsequently used to conduct tests of measurement reliability. Simple correlations among all variables were performed to derive a correlation matrix and simple correlation plots. From visual examination of

the correlation plots of flexibility measures with economy, those flexibility measures having a rational association with running economy and a correlation value greater than ± 0.50 ($P < 0.05$ given the null hypothesis that $r = 0$) were entered into a forward stepwise regression analysis. This analysis was conducted to determine the proportion of variance in running economy explained by one or more flexibility measure(s).

RESULTS[^]

Descriptive and reliability statistics for running economy and trunk and lower limb ranges of motion are presented in [Table 2](#). In general, repeated economy and flexibility measurements were quite stable. Paired two-tailed t-tests showed no significant differences between repeated economy and flexibility measurements, with the exception of sit-and-reach flexibility, which increased consistently on the two recorded assessments (sit-and-reach trial 3: [horizontal bar over]X = 1.66 ± 10.2 cm versus sit-and-reach trial 4: [horizontal bar over]X = 3.00 ± 10.7 cm beyond the toes). Consequently, only the longer, fourth sit-and-reach flexibility values were used in the correlational analyses. Intraclass correlation coefficients calculated for all flexibility measurements indicated that all but one reliability value (plantarflexion) exceeded $R = 0.90$. Hence, measurements of the flexibility variables were generally stable as assessed.

TABLE 2. Descriptive and reliability statistics for submaximal $\dot{V}O_2$ and flexibility measurements.

Correlational statistics for flexibility measures and running economy are presented in [Table 3](#). These analyses revealed that standing external hip rotation and dorsiflexion flexibility measures were positively and significantly associated with submaximal $\dot{V}O_2$ such that less flexible runners (on these two measures) showed a reduced aerobic demand during running (e.g., better running economy). Heel-to-buttock and knee-to-chest flexibility measurements proved ineffective at predicting possible differences in running economy. Only gross assessments were possible (either they could or could not perform the stretch maximally) and participants performed homogeneously on these variables.

TABLE 3. Correlations for submaximal $\dot{V}O_2$ and flexibility measures.

Because dorsiflexion and hip flexibility assessment measures correlated significantly with submaximal aerobic demand, only these measures were entered into a forward stepwise regression analysis for prediction of submaximal $\dot{V}O_2$. The analysis resulted in an R^2 of 0.47 ($F = 7.14, P < 0.01$), indicating that 47% of the variation in running economy was explained solely by variance in dorsiflexion and standing external hip rotation flexibility.

DISCUSSION[^]

Choice of Subjects and Test Velocity[^]

Competitive, rather than recreational, runners were selected for this study because it was thought that a) findings would be specific to other competitive runners, for whom the issue of running economy is particularly relevant; and b) the running gait patterns of competitive athletes were hypothesized to be more stable, and therefore less likely, to vary during running economy assessment. Male, rather than female, sub-elite runners were selected because of greater subject availability. The selection of $4.13 \text{ m}\cdot\text{s}^{-1}$ as the test velocity for assessing running economy was determined by the need to keep the speed pertinent to competitive training and racing paces, and the necessity of ensuring that metabolism remained aerobic. To ascertain whether or not the test velocity was submaximal for all participants, the oxygen demand of running was compared to peak oxygen uptake values obtained in the $\text{VO}_{2\text{max}}$ tests. Calculations revealed that the participants ran at an intensity averaging $68\% \cdot \text{VO}_{2\text{max}}$ (range of 58-79%). Daniels and Gilbert (14) have reported that running velocities resulting in an oxygen uptake of $80\% \cdot \text{VO}_{2\text{max}}$ are submaximal, and sustainable for time periods longer than 3 h for well-trained runners. An additional verification of aerobic running intensity was conducted by examining respiratory exchange ratios (RER) calculated from data collected during the running economy assessments. No RER values exceeded 1.00 (horizontal bar over X = 0.93), ± 0.03 , suggesting that the subjects were using aerobic pathways of energy production for running.

Measurement Reliability[^]

Studies show that high reliability values are obtained when repeated flexibility measures are determined within a short time interval (17) by a single investigator (3,26,31,32) who carefully follows standardized procedures (16,18,19). These findings were noted and incorporated into the methodology of the current investigation, which may explain why high reliability values were generally obtained.

Selection of Measurements for Further Analysis[^]

Of the nine flexibility assessments conducted in this study, two proved to be of little value for examining the possible relationship between flexibility and running economy. Heel-to-buttock and knee-to-chest measurements did not distinguish between inflexible and flexible participants. Consequently, they were excluded from further analysis. A priori selection of heel-to-buttock and knee-to-chest assessments had been based upon the understanding that quadriceps, hamstring, buttocks, and lower back inflexibility and flexibility might affect running economy by either restricting or enhancing optimal stride length and frequency. While this scenario may still be plausible, heel-to-buttock and knee-to-chest assessments appear too gross to effectively determine the validity of this hypothesis. Interestingly, Gleim and coworkers (20) reported similar results in that the Ely test (quadriceps) and Thomas test (hip flexors) did not distinguish between flexible and inflexible subjects. Of the seven remaining flexibility test measurements, all were continuous and variable. It should be noted, however, that straight leg raise and sit-and-reach measurements were highly correlated ($r = 0.91$). One of the test measures, therefore, may be redundant.

Selection of Variables for Further Analysis[^]

Due to the large number of flexibility measures obtained and small number of subjects tested, it was decided that only flexibility variables that demonstrated some observable and viable association with running economy would be included in the stepwise regression model. To determine which factors warranted inclusion, simple correlation plots of running economy and each of the seven flexibility measures were created. These plots revealed that two variables, dorsiflexion and standing external hip rotation, produced measurements that were positively associated with aerobic demand during submaximal running. Measurements from these assessments indicated that the more inflexible participants were more economical per unit body mass. As noted earlier, Gleim and coworkers (20) reported a similar association between inflexibility and lower submaximal aerobic demand. In their study, all but two of the 11 tests administered showed tight individuals with a lower $\dot{V}O_2$ than loose subjects.

Based upon this study's findings, dorsiflexion and standing external hip rotation measures were entered into a forward stepwise regression model, which resulted in an R^2 of 0.47. This value indicates that 47% of the variance observed in running economy was predicted solely by dorsiflexion and standing external hip rotation flexibility measures. In considering mechanisms by which these variables may affect running economy, dorsiflexion inflexibility could lower submaximal aerobic demand by enhancing elastic energy storage and return in the Achilles tendons and calf muscles of the legs. External hip rotation inflexibility could also enhance running economy by stabilizing the pelvic region of the body at the time of foot impact with the ground, thereby reducing the need for excessive and metabolically expensive stabilizing muscular activity.

It is unclear why the remaining flexibility variables showed no positive or negative association with running economy. Possibly, the flexibility tests performed assessed flexibility measures irrelevant to the aerobic demand of locomotion, although this was believed initially not to be the case. It is also possible that the test velocity of $4.13 \text{ m}\cdot\text{s}^{-1}$ was too slow for certain areas of trunk and lower limb inflexibility to become limiting factors. Conceivably, reduced lower limb flexibility (inflexibility) at high speeds could increase submaximal $\dot{V}O_2$ by forcing the body to utilize excessive muscular activity to maintain appropriate stride lengths and leg turnover rates. Thus, at faster speeds, inflexibility could result in worse economy. Finally, it is possible that associations between certain flexibility measurements and running economy were not revealed because of homogeneity in measures of flexibility and running economy. Examination of the raw data and flexibility versus running economy plots suggests, however, that this is not a likely explanation. Running economy varied by approximately 20%, and all flexibility measures varied by at least that much.

It should be understood that running economy is generally thought to be a multicomponent construct (12,27). As such, it may be influenced by kinematic, anthropometric, and cellular variables not measured in this investigation. Calculations performed in this study showed that variability in dorsiflexion and standing external hip rotation accounted for 47% of the variance observed in running economy. That figure also reveals that 53% of the variance in submaximal aerobic demand remains unaccounted for.

CONCLUSION[^]

Results of this study suggest that inflexibility in hip and calf regions of the musculoskeletal system is associated with improved running economy in sub-elite male distance runners. Although speculative, potential mechanisms by which inflexibility may be related to a lower submaximal $\dot{V}O_2$ include minimization of the need for muscle stabilizing activity and increased storage and return of elastic energy. At present, inflexibility in the legs and trunk is assumed by clinicians to be associated with a higher risk running injuries. With this point in mind, runners should beware of concluding that general inflexibility is distance-running performance.

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SUBMAXIMAL AEROBIC DEMAND; DORSIFLEXION; STANDING EXTERNAL HIP ROTATION