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Arch Stiffness Does Not Determine Running Economy in Recreational Runners

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ABSTRACT

International Journal of Exercise Science 16(2): 402-410, 2023. The primary purpose of this study was to determine the relationship between foot length, arch stiffness, and running economy in recreational runner at low running velocities. Sixteen trained endurance (age 20.5 ± 0.4 yrs, height 172 ± 1.8 cm, and mass 68.53 ± 2.40 kg) athletes had their foot anthropometrics and running economy measured. Foot anthropometrics including Foot Length (FL), Arch Stiffness Index (ASI), and Achilles Tendon Moment Arm Length (ATML) were assessed. Subjects then completed a maximal oxygen consumption (VO_{2max}) test and running economy (RE) assessment. RE was measured as the oxygen consumption during running at velocities of 9.9 km/h and 11.9 km/h at a 1% grade. Data is reported as Mean ± SE, and the relationship between foot anthropometrics and running economy was assessed with linear regression (α = 0.05). Results: Absolute and relative VO_{2max} values were 3.68 ± 0.19 L/min and 52.96 ± 1.51 mL/kg/min. ASI was 1513 ± 174.27 A.U. with a standing foot length of 25.41 ± 0.4 cm. Subject oxygen consumption at 9.9 km/h and 11.9 km/h was 34.9 ± 0.80 mL/kg/min and 41.02 ± 0.82 mL/kg/min, respectively. There was no correlation between ASI, FL, AHI, and RE (p > 0.05). Arch stiffness and Achilles tendon moment arm do not determine running economy. Therefore, running economy may be impacted by other physiological and biomechanical factors at low running velocities.

KEY WORDS: Endurance performance, moment arm, oxygen cost

INTRODUCTION

Running economy is the steady-state oxygen consumption (VO_2) at a given running velocity, and is an important determinant of endurance running performance capabilities (8). However, running economy can vary up to 30-40% among well-trained runners (5, 9). Currently, no single physiological or biomechanical variable has been found that completely predicts running economy; consequently, it appears that running economy is more likely the result of the integration of several variables (1).

It is hypothesized that VO_2 for a given velocity would be 30-40% higher if not for the elastic energy storage and release during running (3). The arch of the foot can store and return 17% of the mechanical energy transferred from the body to the ground because of its function as a spring during running (15). Additionally, peak ankle moment generated during running is negatively correlated with RE, which is influenced by the longitudinal stiffness of the shoe as subjects with a 'stiff' sole had approximately a 1% improvement in RE (21). Additionally, shoes which artificially increase the longitudinal stiffness through carbon fiber plating have been shown to improve RE by ~4%, further supporting the relationship between longitudinal arch stiffness and running economy (13). However, the role of foot arch stiffness itself in determining running economy is currently not known.

Achilles tendon moment arm length is negatively related to running economy (2, 19, 22). Moment arm length explains 56-80% of the variation in running economy in heterogeneous groups of well-trained endurance runners (2, 19, 22), such that individuals with a smaller moment arm require less energy for a given running velocity. The increased running economy from a shorter moment arm may be due to the increased ankle peak moment (22), as studies examining peak ankle moment have found significant negative correlations to RE (2). However, prior research examining ATML and RE have done so in groups of highly trained runners at high testing velocities (16 km/h). However, this pace (16 km/h) equates to > 90th percentile in 1.5 mile run times (6), a pace that exceeds the submaximal capabilities of most trained recreational runners. It is unclear the role ATML plays in RE at lower running velocities which are common among trained recreational runners. Furthermore, examining the relationship between ATML and RE at lower running velocities will help determine if the relationships found in prior studies are independent of running velocity.

Therefore, the primary purpose of this study is to determine the relationship between foot characteristics including: arch stiffness, and Achilles tendon moment arm length and running economy in recreational runners. We hypothesized stiffer arches of the foot and shorter Achilles tendon moment arms would be related to greater running economy.

METHODS

Participants

A convenience sample of sixteen recreationally trained endurance athletes provided informed consent to participate in this study. Their eligibility was determined by Health History Questionnaire ensuring that all participants had a prior history of aerobic training and were free of any lower extremity injury. Nine of the subjects were male, with seven females. The subjects were 20.5 ± 0.4 years old, 68.5 ± 2.4 kg in body mass, and 172.0 ± 1.8 cm tall. All subjects provided written consent and the study was approved for human subject testing and performed in compliance with all protocols and ethics of the West Virginia University Institutional Review Board, and conducted in accordance to the ethical standards of the *International Journal of Exercise Science* (18).

Protocol

Two separate testing visits were required, and all testing was conducted at the WVU Exercise Physiology Laboratory. The first visit included the completion of the Health History Questionnaire and informed consent, along with the measurement of all descriptive characteristics, foot and ankle anthropometrics, maximal oxygen consumption testing, and running economy familiarization. At least 48 hours later, subjects returned to the laboratory and completed the running economy testing. To minimize potential bias throughout the data collection procedures foot anthropometrics and running economy were calculated by independent trained laboratory technicians and the technician responsible for foot anthropometric data processing/analysis was blinded to the results of the running economy testing.

Foot Anthropometrics and Arch Stiffness Index: Foot length, arch height index (AHI), and arch stiffness index (ASI) was measured using the Arch Height Index Measurement System (JAK Tools; Cranberry, NJ). Briefly, subjects foot length, dorsum height, and truncated foot length were measured during seated and standing trials. Foot length was determined from the most anterior aspect of the foot to the most posterior aspect. Truncated foot length (TFL) was measured as the distance from the most posterior portion of the calcaneus to the center of the first metatarsophalangeal joint, while dorsum height was measured using the at the foot instep position, 50% of the foot length. AHI was determined in seated and standing positions and determined using Equation 1 below, and used to calculated ASI based on prior studies using Equation 2 below (24). Seated measurements were collected while the subject was seated with the right foot elevated on wood blocks, leaving the medial longitudinal arch unsupported. Standing measurements were collected while standing with weight evenly distributed between both legs: right foot resting on elevated wood blocks and left leg resting onto a scale to ensure even distribution. Measurements were recorded to the nearest 0.1cm and the average of two measurements was determined.

$$(1)\ AHI = \frac{Dorsum\ height\ at\ 50\%\ FL}{Truncated\ FL}$$

$$(2)\ ASI = \frac{(0.4 \times bodyweight)}{(AHI(sitting) - AHI(standing))}$$

Achilles Tendon Moment Arm: Achilles tendon moment arm length (ATML) was defined as the shortest distance between the Achilles tendon to the center of rotation of the ankle. A reflective marker was placed in the most centrally prominent portion of the medial malleolus after palpation. Each subject placed their foot onto wooden blocks with the lateral edge of their foot aligning with the block, containing a reference ruler. This allowed their medial malleolus to be positioned in the same sagittal plane as the reference block. A photograph was then taken from the sagittal plane of the foot using a digital camera (GeekPro 12MP Action Camera). A scale was set using the reference ruler for each photo to convert pixels to centimeters. Each image was uploaded to the digital software ImageJ to calculate ATML. The horizontal distance between the marked portion of the medial malleolus and the most posterior portion of the Achilles tendon was determined in the picture (2, 19, 22).

Maximal Oxygen Consumption: Subjects exercised for 8-12 minutes at a constant self-selected velocity, with the treadmill incline increasing to fatigue based on previous methods (7, 16). Subjects initially ran at a 0% incline which was increased to 4% at minute 4 and an additional 2% every 2 minutes thereafter. If subjects reached 10 minutes of test time, the work rate increased 2% every minute until exhaustion. The highest 30s average of oxygen consumption (VO_2) was used as the measurement ofVO_{2max}. Maximal rating of perceived exertion (RPE) > 17, maximal heart rate ± bpm of age-predicted max (23), and respiratory exchange ratio (RER) > 1.1 was used to determine successful test. Heart rate was measured continuously with a strap worn around the chest (Polar H10, Polar, USA).

Running Economy: Running economy (RE) was determined as the rate of oxygen during submaximal exercise. The economy protocol consisted of two 5-minute stages at velocities of 9.9 km/h and 11.9 km/h. The treadmill was set to 1% throughout the duration to accurately reflect the energetic cost of true outdoor, ground, or road running (14). RE was recorded from the average VO_2 in the final minute of each stage of testing. Subjects completed all trials in their own running shoes.

Respiratory Gas Analysis: Respiratory analysis was conducted using an automated metabolic measurement system (Parvo Medics TrueOne 2400), with the subjects breathing through a one-way valve (Hans Rudolph, Kansas City, MO, USA). VO_2, VCO_2 and RER were continuously monitored throughout each exercise test.

Statistical Analysis

All data are reported as Mean ± SE. Linear regression analysis was performed to determine the relationship between independent variables (FL, AHI, ASI, and ATML) with running economy at various velocities. Paired t-tests were conducted to determine differences in economy data at various velocities, and foot anthropometrics during seated and standing trails, with significance set *a priori* at $p < 0.05$. Cohen d effect size measures were determined for all paired t-tests (4). All statistics were performed using GraphPad PRISM 9 software (GraphPad Software, San Diego, CA).

RESULTS

Results of maximal oxygen consumption testing can be found in Table 1 below.

Table 1. Results of maximal oxygen consumption testing.

	Mean ± SE
Absolute VO_{2max} (L/min)	3.68 ± 0.19
Relative VO_{2max} (mL/kg/min)	52.96 ± 1.51
Heart Rate (bpm)	198 ± 1
Respiratory Exchange Ratio	1.12 ± 0.01
Rating of Perceived Exertion	18 ± 2

There was no correlation between ASI, AHI, FL, or ATML and RE ($p > 0.05$). Figure 1 (panels A-F) below show graphical representation of correlations at 9.9 km/h and 11.9 km/h, respectively.

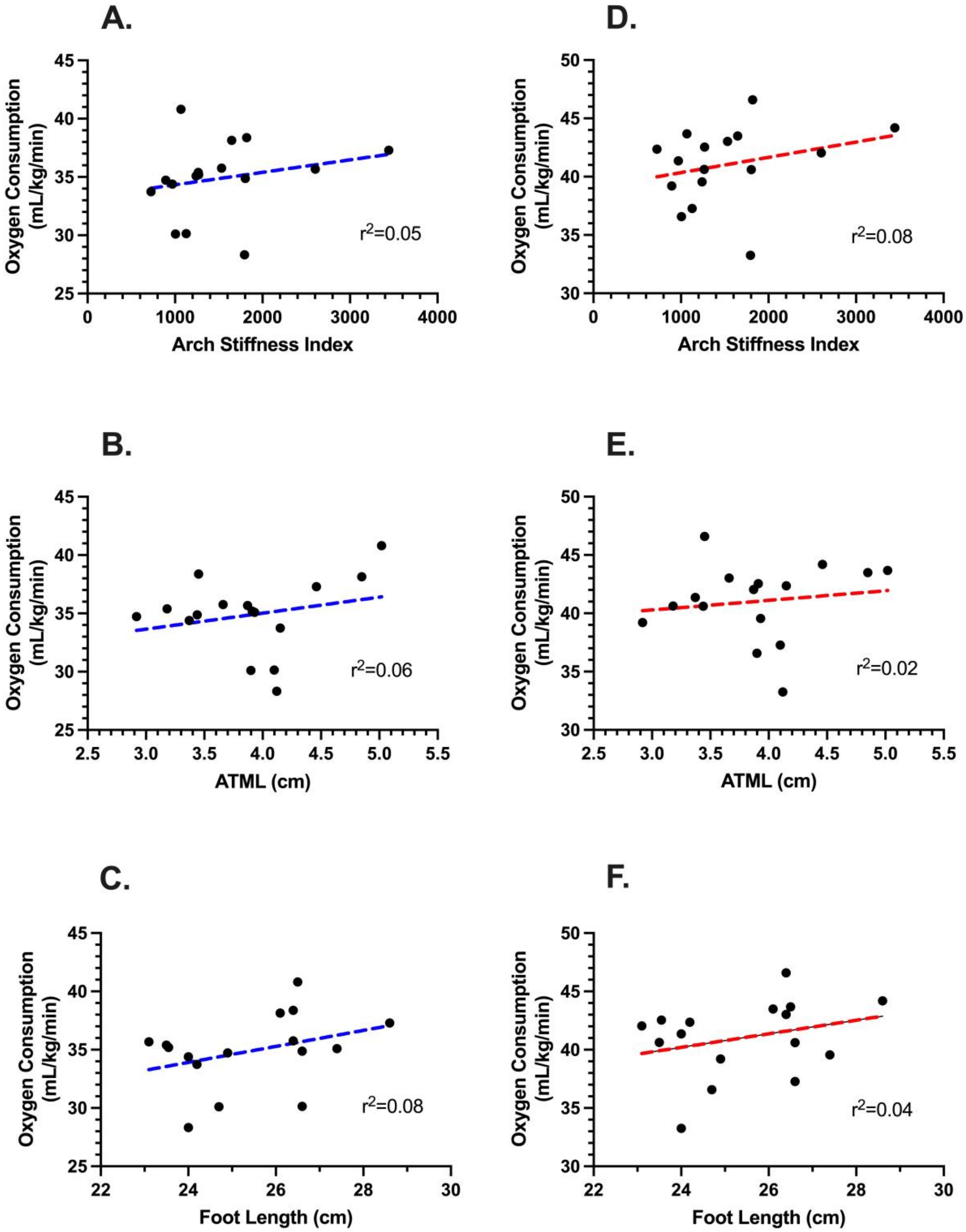

Figure 1. Relationships between Arch Stiffness Index, Achilles Tendon Moment Arm Length, Foot Length and Oxygen Consumption while running at 9.9 km/h (Panels A-C) and 11.9 km/h (Panels D-F). Blue and red dashed lines represent linear regression best-fit for 9.9 km/h trial and 11.9 km/h, respectively

Subjects ran at 9.9 km/h and 11.9 km/h which elicited ~66% VO_{2max} and ~77% VO_{2max}, respectively. As work rate increased there was an increase in: oxygen consumption, RER, HR, and RPE ($p < 0.05$). Full running economy data can be found in Table 2, see below.

Table 2. Results from running economy testing at both 9.9km/h and 11.9km/h.

	9.9 km/h	11.9 km/h	Effect Size (*d*), *p*-value
Relative VO_2 (ml/kg/min)	34.88 ± 0.804	41.02 ± 0.825	4.06, $p < 0.01$
Heart Rate (bpm)	163 ± 5	181 ± 4	1.85, $p < 0.01$
Respiratory Exchange Ratio	0.87 ± 0.01	0.96 ± 0.01	2.45, $p < 0.01$
Rating of Perceived Exertion	9 ± 0	13 ± 1	2.18, $p < 0.01$

Foot anthropometrics during seated and standing trials can be found in Table 3, see below. Mean ASI and ATML were 1513 ± 174.27 A.U. and 3.9 ± 0.14 cm, respectively.

Table 3. Foot anthropometrics during seated and standing trials.

	Seated	Standing	Effect Size (*d*), *p*-value
Foot Length (cm)	25.28 ± 0.34	25.61 ± 0.40	1.76, $p < 0.01$
Truncated Foot Length (cm)	18.33 ± 0.31	18.55 ± 0.31	0.83, $p < 0.01$
Dorsum Height (cm)	6.53 ± 0.12	6.25 ± 0.12	-2.59, $p < 0.01$
Arch Height Index	0.338 ± 0.006	0.357 ± 0.006	2.71, $p < 0.01$

DISCUSSION

The primary purpose of this study was to determine the relationship between foot characteristics including arch stiffness, and Achilles tendon moment arm length and running economy in recreational runners. The results of this study suggest running economy is not related to arch stiffness of the foot or ATML in recreational runners. These data disagree with the hypothesis that longitudinal stiffness of the foot and shorter moment arms improve running economy.

Due to prior research suggesting large increases (30-40%) in energy expenditure with removal of elastic energy storage during running (3), and the longitudinal arch of the foot's capability functioning like a spring (15), we hypothesized that a "stiffer" arch of the foot would improve running economy. However, we found no relationship between ASI and RE in this study. This is in disagreement with prior research which artificially increased longitudinal stiffness of the foot through carbon fiber plating (13); however, resent research which has "cut" the carbon fiber plating therefore reducing the effect of carbon fiber plating did not significantly impact the running economy of the shoes (12) suggesting stiffening of the foot may play a limited role in running economy.

Contrary to prior studies which found shorter Achilles tendon moment arms are related to lower oxygen cost during running (2, 19, 22) we did not find a significant correlation between ATML and RE. A shorter moment arm can improve tendon energy and therefore reduce oxygen cost during running (19, 22). The lack of correlation between ATML and RE in our study may be a result of the testing velocities used in our study of recreational runners. Prior studies which have found strong relationships between ATML and running economy utilized higher testing velocities of 16 km/h (2, 19, 22). However, prior studies found no relationship between ATML and RE at lower testing velocities (e.g. walking at 5.4km/h)(19). It is possible that ATML influences RE at higher velocities (≥ 16 km/h)(2, 22), but at lower testing velocities a shorter moment arm may not reduce oxygen cost (19). Therefore, future studies should examine the relationship of ATML across a range of testing velocities to better understand the role of ATML in determining RE.

A limitation of the current study is not characterizing foot strike pattern while running. Foot strike may play an important role in determining the elastic properties of the foot (17). With a rear foot strike the heel comes in contact with the ground first and contact is transferred posteriorly to anteriorly. This movement pattern does not place as much "stretch" on the longitudinal arch of the foot during initial contact and may inhibit the elastic properties of the foot arch (17). However, with a mid-foot and fore-foot strike the ball of the foot contacts the ground before the heel or at the same time and places greater strain on the longitudinal arch and potentially increases the elastic properties of the foot. Therefore, longitudinal arch stiffness may influence running economy in individuals with a mid to forefoot strike pattern and future studies should examine the interaction of foot strike pattern, arch stiffness, and running economy. Additionally, subjects in our study performed the running economy tests in their personal shoe wear and sole inserts, as we were unable to control for running footwear. Specific running shoe design has been shown to play a role in RE (10, 11, 20). Cushioning in shoes can result in a 2.8% variability in aerobic demand in treadmill running (10). This may have an influence on the overall findings as an individual's running shoes or sole inserts may mitigate the resulting effects of the stiffness of their arch. Furthermore, our subject group did not demonstrate a wide variation in running economy with ~56% of subjects within a 2.0 ml/kg/min VO_2 range (33.7 - 35.7 ml/kg/min) while running at 9.9 km/hr. This restriction in range of economy may have prevented us from finding a correlation between ASI, ATML, and running economy.

In conclusion, it appears that foot anthropometric characteristics, specifically ASI and ATML do not play a significant role in the determination of overall running economy in recreational runners at low running velocities. It is likely that running economy may not be influenced by one variable or characteristic, but by a collection of variables interconnected amongst physiologic and biomechanical systems. Future research examining the potential role of ASI and ATML should consider examining the interaction of these variables with running velocity, shoe, and foot strike type on running economy.

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