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Anthropometric Determinants of Economical Runners

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Anthropometric Determinants of Economical Runners

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Abstract

Anthropometric Determinants of Economical Runners

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The University of Texas at Austin, 2016

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Abstract:

Running economy is one of the most important factors in predicting performance in distance running, especially in elite runners. A substantial difference, (e.g.; 30-40%) in running economy can be seen even among elite runners. While economy has traditionally been tested at 240-268 m/min, these paces are slower than those of elite runners in competition. It was hypothesized that various anthropometric and flexibility variables, previously evaluated in the scientific literature, would more strongly correlated with running economy at speeds in excess of 268 m/min. Considering the link between elastic energy storage and return and the metabolic cost of running, variables that allow for increased storage might be correlated with enhanced running economy. In a group of nine well-trained male runners these variables were examined in relation to running economy measured as oxygen consumption in ml/kg/min during treadmill running at 268 m/min, 290 m/min, 310 m/min and 320 m/min. At 268 m/min, Achilles tendon moment arm and arch stiffness both displayed moderate correlations ($r=0.69$, $p<.05$) and ($r=-0.673$, $p<.05$), respectively) with oxygen consumption. Also, proportional leg length showed a strong negative correlation ($r=-0.85$, $p<.05$) with oxygen consumption at 320 m/min. In conclusion, the present study found smaller moment arms of the Achilles tendon, stiffer arches, and relative leg length to be related to reduced oxygen consumption while running at submaximal paces.

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General Introduction

Running is one of the most basic of all human abilities and is one of the most fundamental actions of most athletic endeavors. Therefore, the speed of running one can sustain is generally a good predictor of success in most of events. There are two ways to increase the speed one can sustain, one must either increase his or her aerobic power or increase the ability to efficiency convert that aerobic power into locomotion (2, 61). Through years of research, methods of increasing aerobic power have been studied extensively and the factors that affect the production of that power have been only partially revealed (65). Meanwhile, factors that aid in efficient use of aerobic power have not been clearly defined, and methods of increasing this efficiency are still debated in scientific literature.

Running economy (RE) is classically defined as the energy demand (oxygen consumption; VO_2) for a given submaximal running speed. When normalized for body mass (ml/kg/min), runners with good economy use consume less oxygen, thus less energy is demanded for a given speed, of running. Running economy has been strongly correlated with performance in distance running competition (16). Within a group of runners with high maximal oxygen consumption values (VO_{2MAX}), running economy has the potential to be the most important determinate of success in endurance running events (24, 32).

Among trained distance runners a 30-40% variance in RE has been shown for a given submaximal speed (16). Variability in RE has been attributed to various biomechanical, physiological, environmental and anthropometric influences. Researchers have identified several anthropometric factors that RE may be affected by which include: stride length and frequency (14, 33), segment lengths (70), body mass or mass distribution (51, 70), flexibility (18, 30) and various tendinous characteristics (40, 61).

While all of these have been tested at common testing paces (240-268 m/min) it is unknown to what degree these relationships persist at paces commonly seen during elite distance running velocities. Currently, many of the highly competitive marathons are consistently seeing the top 15-25 finishers hold paces much faster than those previously tested for the duration of the event. Therefore, it is important to elucidate the relationships to economy at paces that more closely mirror the paces run in these settings. The present work sought to evaluate various anthropometrical differences at high intensities of running, up to 90-95% VO_{2MAX} in which the consequence of these anthropometrical characteristics may be augmented (41).

Research Purpose and Hypotheses:

In this study we evaluated relationships between running economy and anthropometrical and biomechanical measures, such as maximal thigh and calf circumference, length of the moment arm of the Achilles tendon, leg length and proportional leg length, foot arch stiffness, and flexibility measures.

Hypothesis 1: Subjects with smaller maximal thigh and calf circumferences will consume less oxygen at any submaximal running speed.

Hypothesis 2: Subjects with shorter distance from the back of the foot to malleoli will consume less oxygen at any submaximal running speed.

Hypothesis 3: Subjects with longer legs that contribute to a greater proportion of their overall height will consume less oxygen at any submaximal running speed.

Hypothesis 4: Subjects with stiffer arches will consume less oxygen at any submaximal running speed.

Hypothesis 5: Subjects that exhibit less flexibility through the hips and legs will consume less oxygen at any submaximal running speed.

Literature Review

Introduction

Running is among the most innate abilities of human beings and is one of the most fundamental actions in most athletic competitions. For this reason running has become one of the most studied and appreciated subjects in current research. In competitive distance running, there are three variables that have been linked to success. These are, maximal oxygen uptake (VO_{2MAX}), blood lactate threshold or the highest percentage of VO_{2MAX} a runner can sustain without blood lactate accumulation that would have negative consequence on performance, and running economy (RE) (28). Running economy has been classically defined as oxygen cost of a given submaximal speed of running (usually 268 m/min) (17) and more recently, as the oxygen cost of running 1 km (5). Originally, economy was thought to be similar among athletes; however, inter-individual differences in running economy of 20-30% have been reported (24) Only moderate correlations exist between VO_{2MAX} and performance and this correlation was even weaker when examined among groups of runners more homogenous in VO_{2MAX} (23). Thus, among groups with similar VO_{2MAX}, improvements in RE could be as effective in increasing distance running performance as changes in aerobic power (24), and may well be the most effective marker of performance (49). Improvements in economy have been linked to dramatic increases in performance in middle distance and long distance runners (15, 35). Figures 1 and 2, adapted from Morgan et al.(49), illustrate the benefit of improved economy in these groups. Figure 1 shows even with a lesser VO_{2MAX}, Athlete D is able to achieve the same velocity at VO_{2MAX} (vVO_{2MAX}). Further, Figure 2 displays two athletes with similar VO_{2MAX} values yet, the more economical runner (Athlete A) does not reach this VO_{2MAX} until running at a much faster pace compared to the less economical (Athlete B). This different in economy is truly evident when comparing 10km race times, with Athlete A finishing nearly 3.5 minutes ahead of his counterpart.

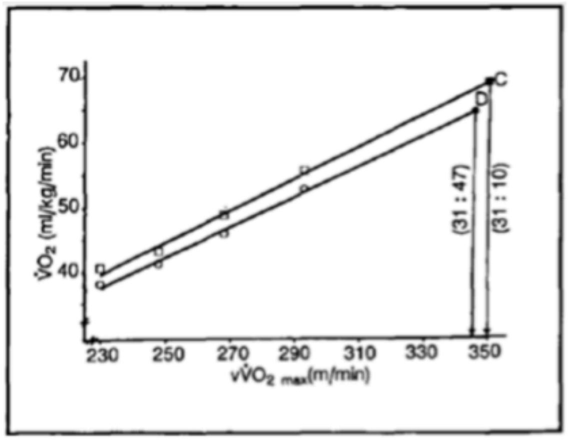

Figure 1 Adapted from Morgan et al. (48) illistrates a practical application of running economy in competition with 10-km time in parenthesis. Subject C with a significantly higher VO_{2MAX} achieves his maximum velocity of running around the same pace as Subject D. Although the latter's VO_{2MAX} is significantly lower, as a result of superior running economy Subject D finishes only slightly behind his counterpart in a 10-km race

Testing for RE has been the subject of some thought, due to the need to improve the reliability and applicability of laboratory testing on a treadmill to running in competition over ground. To account for environmental factors, such as

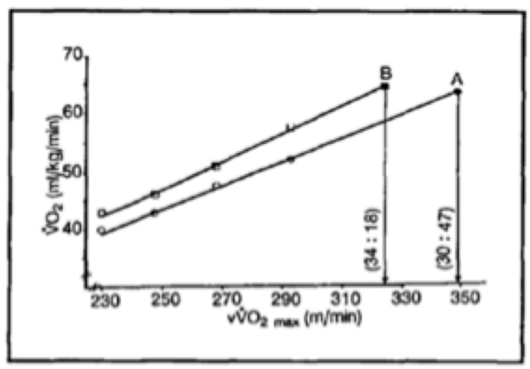

Figure 2 Adapted from Morgan et al. illustrates a practical application of running economy in competition with 10 km times in parenthesis. The subjects in this figure have similar VO_{2MAX} values, yet Subject A achieves max at a much higher velocity of running. As a function of superior running economy Subject A finished a 10 km race over 3.5 minutes faster than Subject B.

wind, and increased use of the hamstrings in over-ground running; laboratory treadmills are usually set to a 1% grade during testing (60). Economy has also been shown to be stable from day to day. Intra-individual variations of 1.5-5% have been consistently shown (50). Through study of running economy it has become appreciated as a multifaceted interaction of many factors (49) of which anthropometric variables seem to be of merit. As such this review will focus on the breadth of knowledge current research has amassed on these anthropometric relationships with running economy.

Mass

One of the most obvious variables to examine is mass. As such, mass and mass related variables have been studied extensively. In an early investigation Taylor (63) showed an inverse relationship between the cost of running and body size in many terrestrial animals. This group further illustrated this point by showing that the economy of motion in mice is significantly less than that of larger animals such as a pony or elephant(63). The cost of running, expressed per kg of body weight, decreases with increases in mass in humans as well (5). Although no measures of economy were obtained, Oyster and Wooten (52) proposed a positive correlation between RE and ponderal index, or body weight divided by height. In addition, Dotan et al. (27) presented a moderate positive correlation ($r = 0.57$) between the more commonly used body mass index or BMI and running economy, defined as a low VO_2 for a given speed of running. These relationships have been supported by many studies in many subject populations with different training and running experience(2, 6, 25). Daniels (25) showed males to be more economical than females but stated that the discrepancy he found was a function of size. Other researchers have used body mass induced differences in RE to explain the difference in running economy seen between adolescents and adults (6). Currently, many investigators assert that economy data (VO_2) is most representative of the actual economy of the athlete when scaled and presented as ml/kg$^{.75}$/min (56, 59, 64).

Mass Distribution

While many have shown mass to have weak to intermediate correlations to running economy, some hypothesized that the improved economy may not be a function of total mass but the distribution of that mass on the body (51). This thought is based in physics, and larger moment of inertia caused by mass distributed more distally on a segment. Some researchers suggested that somatotyping runners could give insight into more economical running. They suggested most economical runners could be characterized as ectomorphic or ectomesomorphic in body type (55, 72). Cavanaugh and Kram (12) proposed distribution along the segments, especially the legs. Negative correlations exist between both max thigh circumference and maximal calf circumference and economy (71). Taylor et al. (63) opposed this thought and showed in another animal study found no difference between animals with varying masses and distribution despite differences in moment of inertia up to 30 fold. Despite these findings in animal models there have been numerous studies that support this hypothesis in people. Cureton (19) showed oxygen cost increased when external weights were added to the extremities. Some research suggests shoe weight could potentially cost a large increase in oxygen cost with the addition of as little as 50 grams causing approximately 1% increase in the oxygen cost of running (7, 37). Myers & Steudel (51) added weight to the trunk, upper thigh, upper shank and ankle and found increasing cost of running as the weight was moved distally on the limb. Martin et al. (46), in a study of 15 highly trained runners, found that the VO_2 necessary to achieve steady state running at a moderate intensity was almost two times greater when weight was added to the foot compared to when added to the thigh.

Stride Length and Width

It is generally assumed that swinging of the extremities accounts for a great deal of the cost of running. As such, much research has evaluated alterations in gait to optimize the economical transfer of aerobic power to translocation. Some early research suggested that more skilled runners exhibited longer strides (26). Others have since observed that, when grouped by performance, elite distance runners took shorter strides than good distance runners (13). Through observation of Olympic marathoners, Daniels (22) was in agreement that the more successful athletes took shorter strides during Olympic competition. These early studies served as a basis for studies to follow. Although they seemed to relate these shorter strides to performance, there was no economy data taken from these groups to establish concrete differences. In studies comparing stride length related to height, relative or absolute, only low to moderate correlations could be found (14, 39, 70). The view of most experts in the field today is that the best stride length is the length that is self-selected by the athlete (14, 33). It has been suggested that freely chosen stride characteristics is the most economical through an integrated of the athlete's rating of perceived exertion and that over time this modifies the natural stride length to its most economical distance (12). Kaneko (39) also showed this to be true in regards to stride frequency. In the only significant case with results to these findings, Morgan (48) found runners who had self selected a pattern of over-striding did see a benefit in economy from stride length optimization.

Foot Strike Pattern

In current literature the relationship between foot strike patterns and running economy remains unclear. Cross sectional studies have shown that as much as 75 % of marathon runners are rear foot strikers, with the much of the remainder being mid-foot strikers, and even less fore-foot strikers (57). Yet, within the top half of finishers 36.0% and 2.0% of runners were mid-foot and fore-foot strikers respectively (57). In addition, elite level runners typically use racing flats and are predominantly mid- and fore foot strikers.

Early investigations found no difference between foot strike patterns and even suggested that a rear-foot strike pattern may be advantageous(70). More recently, Perl et al. (53) found when parameters of shoe weight, strike angle, stride rate, and stride length are controlled there is a 2-3% improvement in running economy in the mid-foot and fore-foot strike patterns. Further investigation is needed to elucidate any associated variables, like the effect of each of these patterns has on the elastic properties of the tendons in and around the foot and ankle.

Segment Lengths

Along the same school of thought, it stands to reason that increased segment length would also cause increased moment of inertia about the joint and theoretically increase the cost of running. Early observational studies in Olympic distance runners differed (45, 62). Tanner (62) claimed distance runners were short-legged while Malina et al. (45) suggested female distance runners exhibited a long-legged habitus. Distance runners have been show to exhibit better RE than middle distance and sprinter counterparts (6, 38, 54) but the influence of leg length has only been studied sparsely. In a large group of trained runners, Foster et al. (29) showed a weak correlation between leg length and economy but when presented as a proportion of total body height the strength of the correlation rose (r= 0.54). Foot length and pelvic width have also been indicated as variables that are negatively correlated to RE in elite distance runners (68). Williams and Cavanaugh (70) grouped runners into tertiles on the basis of economy and found no differences in anthropometric measures between the groups. Due to the relative scarcity of studies on segmental length that have actually reported economy data, there is a need for more study on this topic to come to any definitive conclusions to the effect of these variables.

Flexibility

Several groups contend that flexibility may be an important factor influencing running economy as well. Early work agreed with the common thought that flexibility was desirable to improve performance and showed positive correlation between flexibility and running economy in untrained subjects (31). However Craib et al. (18) found that in well trained runners inflexibility through the hips and calf region was associated with improved running economy. Jones et al. (36) supported this in a study which negatively correlated results on a standard sit and reach test and running economy. Another group (41) supported this and reported that stiffer muscles around ankle and knee enhance RE. Many researchers hypothesize that inflexibility may enhance running economy by stabilizing the joints and thereby reducing the oxygen cost necessary (2). While it is generally accepted that maintaining a certain level of flexibility is desired for injury prevention and various other reasons, it seems that stressing flexibility may be counter productive to athletes who seek to reduce the oxygen cost of running. Muscle stiffness has also been linked to increase return of elastic energy (20).

Stretch Shortening Cycle & Tendinous Characteristics

In recent research, tendon characteristics have become of interest to many scientists interested in the storage and return of elastic energy. It has been shown that elastic energy stored during the eccentric contractions make substantial contributions to propulsion as it is released in the subsequent concentric contraction (11, 12, 67, 73). Although there is not a way of quantifying elastic energy to date, there is a consensus that this plays a significant role in economy of running (10, 12, 42, 44). The Achilles tendon and the tendons that comprise the arch of the foot appear to be the most relevant to elastic energy storage and return while running. Ker et al (40) have estimated that the Achilles tendon and fascia that comprises the arch of the foot can store 35% and 17%, respectively of the kinetic and potential energy gained and lost in a step while running at a controlled speed. In agreement, Alexander (1) found that in a 70 kg man running at 268 m/min more than half of the elastic energy can be stored in just 2 springs.

It has been estimated that VO_2 during running would be somewhere between 30 and 40% higher without the contributions from elastic storage and return (8). While Ker's estimation was at moderate speeds some authors believe that at higher running speeds the elastic recovery outweighs the contractile machinery and accounts for most of the work done (11). Some groups have reported that muscle tendon unit stiffness increases with running speed(11, 41, 58). Rate and magnitude of stretch, level of activation and the resulting stiffness of the musculotendinous unit, length of the muscle at the completion of the stretch and initiation of the succeeding concentric contraction have all been shown to effect elastic capacitance (3, 9, 11).

The moment arm of the Achilles tendon appears to be negatively correlated (r =-.75) with cost of running at 268 m/min (61). This moment arm is the distance from the lateral malleolus to the posterior aspect of the Achilles tendon. While Scholz's work is generally accepted there has been some work contradicting the finding (47), but these studies are in small and conducted in very specific groups which makes it hard to generalize the findings. There may be substantial-inter-individual difference in the ability to store and return elastic energy which may support the idea that these play a significant role in differences in running economy (4, 34, 69).

The arch of the foot acting as spring when running can be responsible for 17% of the storage and return of elastic energy (40). While this seems to be a noteworthy avenue of research very little investigation into this topic has been pursued. Roy et al. (57) showed a 1% decrease in oxygen cost of running when with a "stiff" sole compared to running while traditionally shod. These researchers indicated the longitudinal stiffness of the sole decreased peak ankle moment and thereby augmented RE.

Viewed as a spring, the tendons could theoretically store more energy at higher speeds of running and this would allow for greater return on the subsequent concentric contraction. Daniels et. al. (21) showed linearity of oxygen consumption across all speeds, but showed the slopes of the regression lines decreased at higher running speeds. This is potentially due to the increase in elastic return of energy from the tendons of the foot.

Conclusion of Review of Literature

Although current thesis has amassed a large quantity of studies on the topic of running economy, many questions remain to be answered. Also, many areas deserve more attention to evaluate in detail the contribution of the anthropometrical measures that might improve RE. One of the most pressing is the contribution of these at increased speeds. While most testing is done at 240-268 m/min, there are currently many marathoners are holding paces above those tested in the literature for the full duration of their events. To fully understand the extent of these contributions during such competition, it must be evaluated at an intensity in which mirrors that of the competition in question. There should be systematic evaluation of any training that would allow runners, with limited negative consequence, to modify characteristics such as tendon stiffness and flexibility. Also, finding a way to directly quantify the elastic energy used by an athlete would be very advantageous to understanding this mechanism and its potential role as a crucial method for improving running economy. Finally more work needs to be done to clearly establish relationships between some of the measures in question (i.e. leg length and proportional leg length). While measures like foot length have been debated in the literature, further investigation into associated variables (i.e. Arch height/stiffness and Achilles tendon moment arm) may help to elucidate the actual relationship to running economy, if there is one at all. Furthermore, work should focus on revealing the relationship between and measures of arch stiffness as these have yet to be evaluated.

Methods

Subjects

Nine endurance-trained, male competitive runners ranging in age from 18 – 28 years were recruited from the UT Austin campus and community through word-of-mouth. See Table 1 below for demographic data.

Design

Subjects completed three sessions consisting of a VO_{2MAX} test, a familiarization run, and anthropometric and flexibility session as well as running economy testing in the final session. Subjects completed a health-history questionnaire and provided written informed consent before participation in the study. Prior to each of the runs the subjects refrained from any strenuous exercise and alcohol consumption for at least 24 hours. Subjects were also asked to refrain from consumption of caffeine prior to the run on the day of the test.

Overview of Procedures:

Visit 1:

Health History :

Before subjects were admitted to the study, they were given a brief examination. This examination included filling out a brief Health History Questionnaire, and taking measurements of height and weight.

Maximal Oxygen Consumption:

During this procedure, subjects breathed into a mouthpiece (while wearing a nose-clip) that collected and analyzed the O_2 and CO_2 content of expired air. From this their oxygen consumption was determined and maximal values were identified by taking the of the highest 60 second sample. (VO_{2MAX}). The intensity of exercise was set initially at ~70% of the subjects estimated VO_{2MAX} based on previous race performances. Intensity of running was increased by increasing treadmill grade every 1-2 min. until the subjects were at their maximal effort level and became fatigued. Fatigue is associated with a difficulty or inability to maintain the exercise speed (i.e.; slowed running on the treadmill). The total length of the test was 6-12 min, including a 4-minute warm-up. Heart rate was also measured continuously from a strap worn around their chest (Suunto, Vantaa, Finland).

Visit 2:

Warm up:

Subjects were given 15 minutes to stretch and warm up on the treadmill at their own discretion.

Familiarization Run:

Subjects were asked to perform a familiarization run on the treadmill. This run consisted of four 7-minute stages with a rest period between each stage, lasting approximately 35 minutes. The intensity of exercise was increased for each subsequent stage. The sensation of effort and fatigue during the last 1-2 stages was set to be comparable to a race. During the test, subjects breathed into a mouthpiece, while wearing a nose-clip in order to collect and analyze the O_2 and CO_2 content of expired air. In addition, a heart rate monitor was worn around the chest. This run served to make subjects more comfortable with the testing procedures in the subsequent running economy testing visit. Further, because many of these runners do not normally train on treadmills, a familiarization run was warranted to ensure reliable data in the following visit (50).

Visit 3:

Anthropometric Assessment:

Subjects were asked to allow researchers to assess several body segments (i.e. leg length) and anatomical characteristics (i.e. arch stiffness) and record these data. Subjects were allowed a 5-minute warm up run prior to anthropometric and flexibility assessment, but were asked not to stretch. This was designed to minimize the differences that would occur from different forms or techniques of stretching, and emphasize the natural, physiological limits.

1. Anthropometric measures:

    a. Leg length was measured using fiber-glass measuring tape from the lateral malleolus to the greater trochanter. Proportional leg length was calculated as the fraction of total body height made up by the legs.

    b. Arch Height Index was measured using a rigid steel ruler, accurate to 1mm. Adapted from Zifchock et al. (74), the foot was measured from the back of the heel to the first metatarsophalangeal joint (TFL), and the height of the arch of the foot was measured at half of foot length (AH). Participants were measured both seated and standing with boards placed under the heel and the phalanges and metatarsal heads to enable the arch to move. Navicular height was measured by having participants stand on a hard flat surface and placing a small ink mark on the navicular tuberosity, and measuring the vertical distance between the ground and the mark using a rigid steel ruler. Arch height index was calculated as AH/TFL both standing and seated.

    c. Arch Stiffness Index was measured using arch height measurements (as above) adapted from Zifchock et al.(74) was used to calculate arch stiffness. Arch stiffness index was calculated as (body mass x 0.4)/(AHI-seated –AHI-standing).

d. Achilles tendon moment arm was measured using methods adapted from Scholz et al. (61). Briefly, subjects stood on a measurement block with a line extending from the center of the malleolus to the posterior aspect of the Achilles tendon. A photograph was taken and the distance of the aforementioned line was assessed.

e. Maximal thigh and calf circumference was measured using fiber glass measuring tape along the largest circumferential points on both the thigh and calf regions.

2. Flexibility tests:
   a. Sit and reach: Subjects were seated on the floor with their bare feet against a sit-and-reach box. The subjects then slowly reached forward towards their toes while keeping their legs straight and their hands together. The distance from the toes (zero point) measured in centimeters (positive values were awarded if subjects can reach

beyond their toes, and negative values were awarded if subjects can not reach beyond their toes). The best score from 3-4 attempts (each held for 2 seconds) was recorded.

b. External Rotation of the Hip: Standing external rotation of the hip with hip flexion at 90 [degrees]. Subjects was marked along their quadriceps with lines that connect the head of the greater trochanters and the middle of the kneecaps. Once these lines were drawn, subjects stood with their backs and pelvises firmly against a wall. Directly beneath the subjects and perpendicular to the wall, a line was drawn. While an assistant held the pelvis steady, and subjects were allowed to grasp 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 subjects then actively rotated 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.

c. Dorsiflexion of the foot: Subjects were instructed to lie prone on their backs, knees locked, on a non-padded 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 degrees as the ball of the foot was pushed toward the trunk. The degree of passive stretch was set by the subject, who indicated when the stretch was maximal due to physiological limitation(s) or discomfort.

d. Plantar flexion of the foot: Subjects were instructed to lie prone on their backs, knees locked, on a non-padded table. Using the same lines drawn for dorsiflexion measurement, the goniometer was used to measure the change in angle from 90 degrees as the top of the foot is pushed down and pointed away from the trunk. Again, the degree of passive stretch was set by the subject, who indicated when the stretch was maximal due to physiological limitation(s) or discomfort.

Running Economy:

Subjects were asked to run on the treadmill set at 1% grade for each of several 5-minute stages of running at speeds starting at 268 m/min and increasing for each subsequent stage. Each stage will be separated by 5 minutes of rest. These stages increased by 20 m/min until the oxygen uptake reached 90 - 95% of the subjects VO_{2MAX}. If the subject is unable to complete a stage of running they were asked to attempt a stage at 10 m/min slower that the unsuccessful stage. In the last 2 minutes of each stage, expired gasses were collected and analyzed as described above. Heart rate was also used to assess physiological stress in the last minute of each of these stages through telemetry (as above).

Treadmill belt speed was calibrated prior to each submaximal test and was verified during the first minute of the run for each subject.

Statistical Analysis

To analyze the relationship between running economy and the anthropometric characteristics of the foot and lower leg, we calculated the Pearson correlation coefficients between VO_2 at 4 testing paces and all anthropometric variables. Statistical Package for the Social Sciences (SPSS). A 0.05 level of significance was set for all correlations.

Results

Subjects submaximal VO_2 ranged 12-18% within each testing pace. All nine subjects completed testing runs at 268 m/min and 290 m/min, while only 8 and 7 completed runs at 310 and 320 m/min, respectively. Complete VO_2 data at each testing pace is presented in Table 2. Also, each subject's economy curves are presented in Figure 1.

In the first economy run the pace elicited 77.5± 6.1% of the subjects $VO_{2MAX.}$ At 268 m/min, a moderate positive correlation (r=0.69, p<.05) was found between VO_2 and Achilles tendon moment arm, with moment arm explaining 48% of the variance in VO_2. This relationship between moment arm and VO_2 is shown in Figure 1. A moderate negative correlation (r=-0.673, p<.05) was also found between VO_2 and arch stiffness, with arch stiffness explaining 45% of the variance in VO_2. This relationship is shown in Figure 2. None of the other variables tested showed significant correlations at this pace. r^2 values and p-values for all other variables are listed in Table 3.

At 290 m/min pace 86.1± 6.1% of the subjects VO_{2MAX} was elicited. A strong positive correlation (r=0.73, p<.05) was found between VO_2 and Achilles tendon moment arm, with moment arm explaining 53% of the variance in VO_2.This relationship is shown in Figure 3. While not significant, arch stiffness did show a trend toward significance (p= .051). No other variable tested showed a significant correlation at this pace. r^2 values and p-values for all other variables are listed in Table 4.

At 310 m/min correlations between VO_2 and either Achilles tendon moment arm or arch stiffness were no longer significant. This pace elicited 91.4± 5.5% of subjects $VO_{2MAX,}$ and there were no significant correlations present between any of the measured variables. However, at this pace, proportional leg length presented a trend toward significance ($p = .056$). r^2 values and p-values for all other variables are listed in Table 5.

Of the seven subjects who completed the fourth economy run, 94.0± 5.2% of subject's VO_{2MAX} was elicited. At 320 m/min a strong negative correlation ($r = -0.85$, $p < .05$) was found between submaximal VO_2 and proportional leg length. Other than this correlation no other measured variable showed a significant correlation with VO_2 at that high speed. This relationship is illustrated in Figure 4. r^2 values and p-values for all other variables are listed in Table 6.

Discussion

Running economy was defined as the oxygen cost of a given submaximal speed of running, with lower oxygen cost indicating superior economy. We have previously observed differences in economy in well-trained athletes of 30-40% (16). It was also clear that no one factor could explain these differences entirely (49). In the present paper, we assessed running economy across a range of speeds that more closely reflected the paces held by elite distance runners during competition, compared to those tested frequently in the literature. Several runs were used to determine the relationship between several anthropometric variables and submaximal, steady-state oxygen consumption, or VO_2.

Alexander (1) found that in an average man running at 268 m/min more than half of the elastic energy can be stored in just 2 springs. The first of which in the human foot is the Achilles tendon, which was found to responsible for 35% of elastic energy storage. In the current study, Achilles tendon moment arm was found to have a positive relationship with submaximal VO_2, and this relationship was expected to gain strength as the speed of running increased. This is in agreement with spring-mass model of the human foot offered by Dalleau (20). The prevailing thought in this model is any energy that can be stored in the tendons and returned on the subsequent concentric contraction, will reduce the metabolic cost by reducing the work of the contractile units of the muscle. Indeed, we did find a positive correlation with submaximal VO_2, at 2 speeds therefore a negative correlation with running economy. More specifically, subjects with longer moment arms of the Achilles tendon consumed more oxygen, thereby being less economical than their fellow subjects. This is in agreement with Scholz et al. (61) who found a similar correlation (r=0.75). We also saw an increase in strength of correlation when speed of running was increased to 290 m/min (r=0.73 vs. r=0.69) in agreement with our hypothesis. However, no relationship existed at either of the two subsequent speeds tested.

The second spring mentioned in the human foot is the arch, responsible for 17% of elastic energy storage (1). Arch stiffness was found to have a negative relationship with submaximal VO_2 (e.g. stiffer arch=better economy). This relationship was also expected to grow in strength with increased speed of running. The work of Ker et al.(40) showed storage and return of elastic energy by the fascia of the arch when a force was applied directly. In fact, we did find a positive correlation with running economy at 268 m/min. This is the first time, to the author's knowledge, that this relationship has been shown systematically. However, despite a trend toward significance at 290 m/min this correlation did not persist at any of the higher speeds of running. Our findings are supported by the findings of Roy et al.(57) which showed a decrease in oxygen consumption when wearing a "stiff-sole" shoe versus traditionally shod.

The work of Lieberman and others(43) showed increased arch stiffness in the Tarahumara Indians who chronically ran barefoot, or in minimalist footwear in comparison with their more typically shod counterparts. Juxtaposed with the results of the current study, this may give credence to the theory of improved running economy from chronically training barefoot (66). There has also been work drawing associations between smaller moment arm of the Achilles tendon and stiffer arches with smaller feet (61), with this knowledge we may begin to develop a more definitive dissociation between foot size and running economy.

Proportional leg length, while not significantly correlated to running economy at 268 m/min or 290 m/min, interestingly showed a trend toward significance at 310 m/min (p=.056) and a strong negative correlation at 320 m/min. This was in agreement with our hypothesis. Similar findings have been previously shown at slower paces, as well (29, 49).

No other anthropometric variables measured or flexibility measures showed a significant correlation in the current study, at any speed of running. Although, all have been shown in previous studies (leg length (70), maximal thigh and calf circumferences (51, 70), flexibility through the hips, legs and ankles (18, 30)) none of these correlations existed in the subject population of this study.

The current study did suffer from a small sample size. This lack of power is due to multiple issues, the first of which would be the taxing paces asked of the subjects. Because subjects were asked to run at speeds up to 5-minute-mile pace and each subject had to be capable of achieving each pace aerobically (under 95% of VO_{2MAX}), to ensure accurate running economy data, this drastically reduced the number of runners who could be recruited. Secondly, due to training and the relative proximity to the Olympic marathon trials, which several subjects planned to compete in, there was more attrition than was expected at the outset.

Future research should evaluate all of these variables in a larger subject population, while still allowing for intense paces to be test. Work should also be done to see if these correlations persist in females as well. All though there is no way to quantify energy stored in the Achilles tendon at this time, future research should evaluate this mechanism more closely. Evaluation of moment arm, ankle moments, and the effects of stiffness in the tendon all appear to be warranted. Arch stiffness, the factors affecting it, and its relationship with running economy in different populations are all areas that should be assessed more fully.

Conclusion

Research on running economy and the anthropometric determinants has primarily focused on evaluating economy at speeds that are slower than the paces held in competitive long distance running events. We expanded on the current literature by examining various anthropometrical and flexibility difference at paces that were more similar to those of such events.

Our results support the literature in that the moment arm of the Achilles tendon did show a negative correlation with running economy (VO_2 at 268 m/min). We found a stronger correlation between Achilles tendon moment arm and running economy at 290 m/min, which has not been previously shown. Although a relationship has been shown at slower speeds of running, the current work is the first to significantly correlate proportional leg length to running economy at 320 m/min. We also found positive correlation between arch stiffness and running economy, a relationship that has not been shown in the literature to this point. Further examination of these associated factors and others at fast speeds of running will provide the field information necessary to improve knowledge into this facet of running performance.

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Table 1. Subjects' characteristics.

Subject	Age (yrs.)	Height (cm)	Mass (kg)	V02max (L/min)	V02max (ml/kg/min)
1	25	174.0	64.65	4.887	75.3
2	27	165.1	57.65	4.944	85.8
3	19	177.8	60.1	4.246	72.6
4	18	174.0	62.4	4.288	68.6
5	20	176.5	72.6	4.925	67.9
6	26	194.3	77.9	5.776	74.1
7	22	180.3	77.25	5.308	68.8
8	21	177.8	76.1	4.87	65.2
9	19	177.8	69.75	4.966	69.7
Mean± SD	21.89± 3.3	177.5± 7.8	68.71± 7.8	4.91± 0.5	72.0± 6.1

Table 2. Subjects' VO_2 across all running speeds

Subject	VO_2 at 268 m/min (ml/kg/min)	VO_2 at 290 m/min (ml/kg/min)	VO_2 at 310 m/min (ml/kg/min)	VO_2 at 320 m/min (ml/kg/min)
1	51.3	57.0	61.8	65.4
2	57.1	65.0	71.5	74.0
3	55.6	62.3	68.8	71.5
4	55.9	61.7	64.3	n/a
5	54.4	60.0	62.5	64.9
6	61.1	67.4	70.6	72.0
7	57.7	61.5	65.8	66.6
8	51.4	58.9	n/a	n/a
9	55.2	61.8	65.7	67.8

Table 3. Anthropometric correlations with VO_2 at 268 m/min

Anthropometric variable	r^2	p-value
Height	0.24	0.182
Mass	0.04	0.591
Moment Arm	0.48	0.039*
Arch Stiffness	0.45	0.047*
Sit and Reach	0.27	0.151
External Hip Rotation	0.02	0.744
Dorsiflexion	0.32	0.112
Plantar flexion	0.01	0.813
Max Thigh	0.02	0.731
Max Calf	0.22	0.207
Foot length	0.29	0.135
Truncated Foot Length	0.10	0.398
Leg Length	0.03	0.665
Proportional leg length	0.10	0.4

* Correlation is significant at the 0.05 level.
r^2, explained variance. N, number of subjects.

Table 4. Anthropometric correlations with VO_2 at 290 m/min

Anthropometric variable	r^2	p-value
Height	0.13	0.334
Mass	0.00	0.894
Moment Arm	0.53	0.027*
Arch Stiffness	0.44	0.051
Sit and Reach	0.12	0.360
External Hip Rotation	0.00	0.908
Dorsiflexion	0.29	0.136
Plantar flexion	0.02	0.735
Max Thigh	0.00	0.934
Max Calf	0.15	0.303
Foot length	0.13	0.346
Truncated Foot Length	0.01	0.825
Leg Length	0.00	0.902
Proportional leg length	0.30	0.129

* Correlation is significant at the 0.05 level.
r^2, explained variance. N, number of subjects.

Table 5. Anthropometric correlations with VO_2 at 310 m/min

Anthropometric variable	r^2	p-value
Height	0.02	0.732
Mass	0.01	0.808
Moment Arm	0.20	0.262
Arch Stiffness	0.30	0.160
Sit and Reach	0.00	0.975
External Hip Rotation	0.01	0.791
Dorsiflexion	0.08	0.508
Plantar flexion	0.07	0.531
Max Thigh	0.00	0.941
Max Calf	0.08	0.497
Foot length	0.01	0.868
Truncated Foot Length	0.05	0.595
Leg Length	0.07	0.516
Proportional leg length	0.48	0.058

* Correlation is significant at the 0.05 level.
r^2, explained variance. N, number of subjects.

Table 6. Anthropometric correlations with VO_2 at 320 m/min

Anthropometric variable	r^2	p-value
Height	0.00	0.970
Mass	0.14	0.412
Moment Arm	0.18	0.347
Arch Stiffness	0.33	0.178
Sit and Reach	0.05	0.625
External Hip Rotation	0.01	0.875
Dorsiflexion	0.05	0.625
Plantar flexion	0.18	0.349
Max Thigh	0.14	0.404
Max Calf	0.43	0.110
Foot length	0.02	0.772
Truncated Foot Length	0.16	0.372
Leg Length	0.23	0.276
Proportional leg length	0.72	0.016*

* Correlation is significant at the 0.05 level.
r^2, explained variance. N, number of subjects.

Fig. 3 Relationship between VO_2 and Running Speed in all subjects.

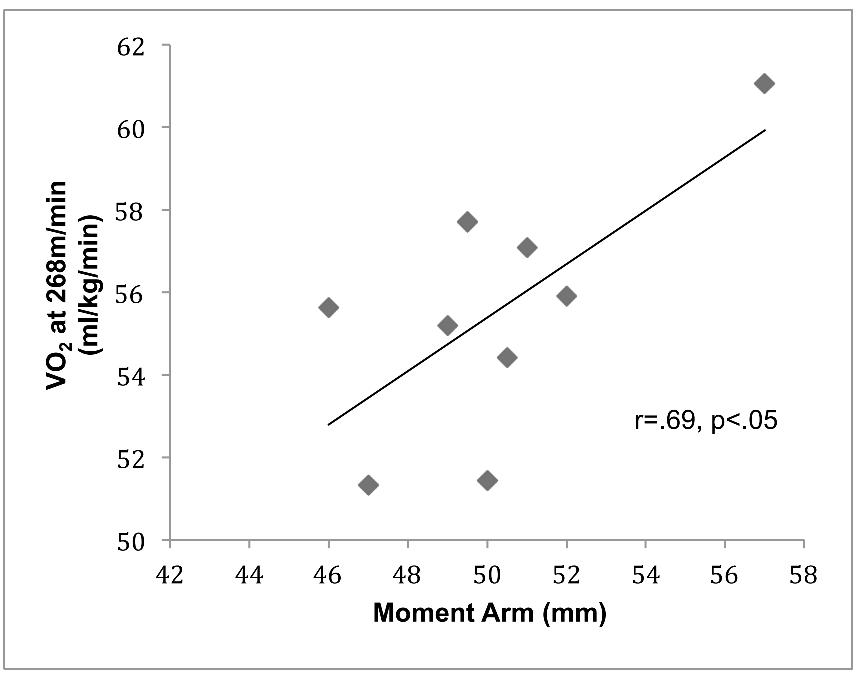

Fig. 4. Relationship between moment arm and oxygen consumption rate (VO_2) in ml/kg/min at 268 m/min. Diamonds are individual participants.

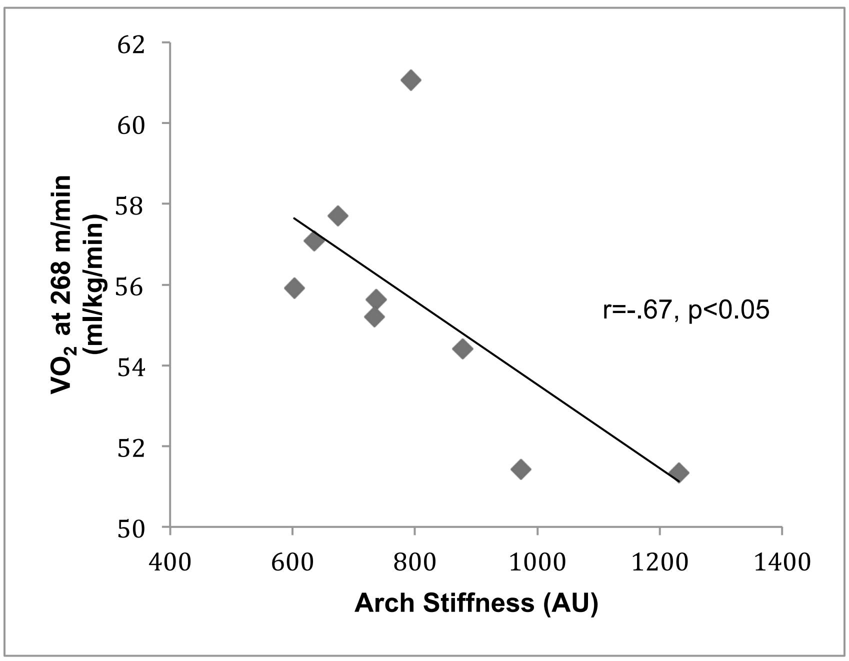

Fig. 5. Relationship between arch stiffness and oxygen consumption rate (VO_2) in ml kg/min at 268 m/min. Diamonds are individual participants.

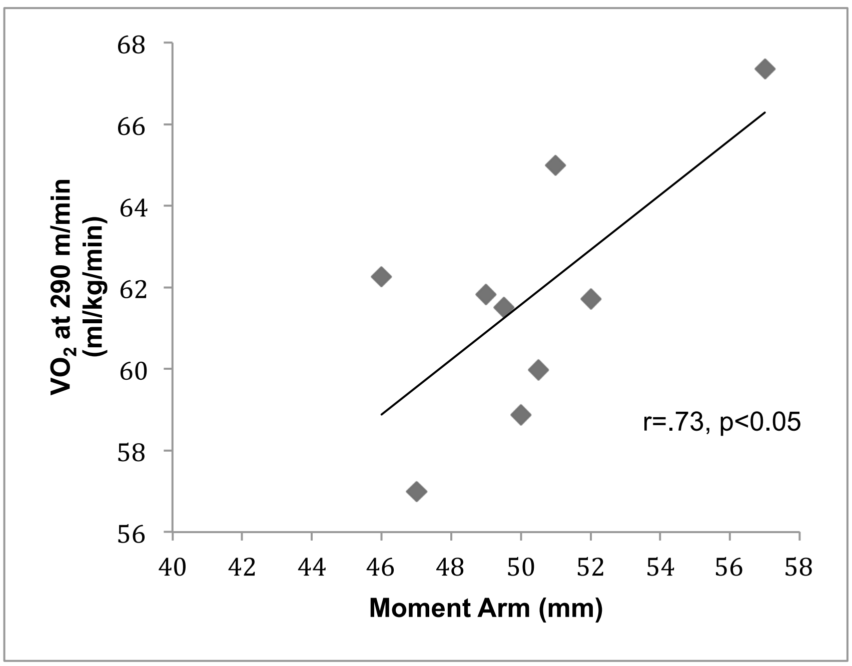

Fig. 6. Relationship between moment arm and oxygen consumption rate (VO_2) in ml/kg/min at 290 m/min. Diamonds are individual participants.

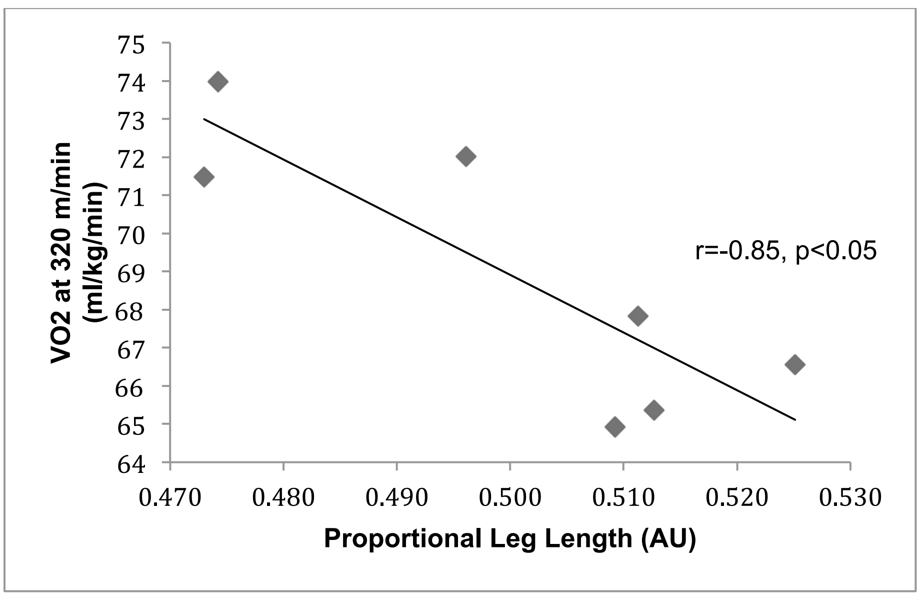

Fig. 7. Relationship between proportional and oxygen consumption rate (VO_2) in ml/kg/min at 320 m/min. Diamonds are individual participants.

Appendix A

Consent for Participation in Research

Title: *Anthropometric Determinants of Running Economy*

Introduction

The purpose of this form is to provide you information that may affect your decision as to whether or not to participate in this research study. The person performing the research will answer any of your questions. Read the information below and ask any questions you might have before deciding whether or not to take part. If you decide to be involved in this study, this form will be used to record your consent.

Purpose of the Study

You have been asked to participate in a research study about the relationship between anthropometrical differences and running economy. The purpose of this study is measure your level of physical fitness for running. These measures can be used to compare your individual attributes to those of previous endurance athletes who have been studied in the Human Performance Laboratory (HPL). We also want to determine in a population of endurance athletes if differences in several anthropometric variables can lead to decreased oxygen consumption for a given velocity of running (i.e.; running economy).

What will you be asked to do?

If you agree to participate in this you will be asked to:

1. Answer a health history questionnaire.
2. Have your maximal oxygen consumption measured during running.
3. Complete a 35-minute familiarization run
4. Have your anthropometric variables measured
5. Complete 5 stages of running at increasing speeds during 30 min of running

This study will entail **3 laboratory visits lasting approximately 1 hour each (3 hours total)** and will include approximately **20** study participants.

<u>Overview of Procedures:</u>

<u>Visit 1:</u>

<u>Health History (~15min):</u> Before you can be admitted to the study, you will be given a brief examination. This examination will include filling out a brief Health History Questionnaire, and taking measurements of your height and weight.

<u>Maximal Oxygen Consumption (~30 min.):</u> You will be asked to perform a maximal oxygen consumption test (VO_{2max}), which will take between 6 – 12 minutes. The intensity of exercise will be increased every 1-2 min. until you are at your maximal effort level and cannot maintain the exercise speed. The sensation of effort and fatigue during the last 1-2 min will be comparable to a race. During the test, you will breathe into a mouthpiece, while wearing a nose-clip, that will collect and analyze the O_2 and CO_2 content of expired air. In addition, a heart rate monitor will be worn around the chest that will be used to monitor heart rate throughout the course of the study. From this data we can determine your VO_2max.

Visit 2:

Warm up (15 minutes): You will be given 15 minutes to stretch and warm up on the treadmill at your own discretion.

Familiarization Run (45 minutes): You will be asked to perform a familiarization run on the treadmill. This run will consist of five 5-minute stages with a rest period between each stage, lasting approximately 35 minutes. The intensity of exercise will be increased for each subsequent stage. The sensation of effort and fatigue during the last 1-2 stages will be comparable to a race. During the test, you will breathe into a mouthpiece, while wearing a nose-clip in order to collect and analyze the O_2 and CO_2 content of expired air. In addition, a heart rate monitor will be worn around the chest. This run will serve to make you more comfortable with the testing procedures in the next visit.

Visit 3:

Anthropometric Assessment (15 minutes): You will be asked to allow researchers to assess several body segments (i.e.; leg length) and anatomical characteristics (i.e.; arch stiffness) and record these data.

Running Economy (45 minutes): You will be asked to perform 5 economy runs. These runs will last 5 minutes with a 5 min rest period between each stage. The treadmill speed will be increased 20 meters/min for each subsequent stage. The sensation of effort and fatigue during this test will be comparable to a 'hard interval-style' run. During the test, you will breathe into a mouthpiece, while wearing a nose-clip in order to collect and analyze the O_2 and CO_2 content of expired air. In addition, a heart rate monitor will be worn around the chest. From this data we can determine your running economy.

What are the risks involved in this study?

This study may involve risks that are currently unforeseeable. Possible risks associated with this study are:

The fatigue test to measure VO_2max will feel like a very short race or a single bout of intense interval training. There is a very small risk that you could experience a muscular injury, such as a muscle strain. It is possible, although very rare, that intense exercise such as performed in this study might cause a heart attack. During the tests, you may stop performing the task at any time for any reason if you feel you need to do so.

What are the possible benefits of this study?

You will receive no direct benefit from participating in this study; however, each subject completing the study will be provided with information about his or her VO_2max, which is useful to running and bicycling training and performance.

Do you have to participate?

No, your participation is voluntary. You may decide not to participate at all or, if you start the study, you may withdraw at any time. Withdrawal or refusing to participate will not affect your relationship with The University of Texas at Austin (University) in anyway.

If you would like to participate please fully read, sign, and return this form to the principal investigator of this study (Heath Burton). You will receive a copy of this form for your personal records.

Will there be any compensation?

You will not receive any type of payment participating in this study.

What if you are injured because of the study?

1. The University has no program or plan to provide treatment for research related injury or payment in the event of a medical problem. In the event of a research related injury, please contact the principal investigator.

2. The University has no program or plan for continuing medical care and/or hospitalization for research-related injuries or for financial compensation.

3. If injuries occur as a result of study activity, eligible University students may be treated at the usual level of care with the usual cost for services at the Student Health Center, but the University has no program or plan to provide payment in the event of a medical problem.

How will your privacy and confidentiality be protected if you participate in this research study?

Each subject will be assigned a unique Subject ID code. This informed consent form and the Health History Questionnaire are the only places where any personal identifying information will be recorded. These forms will be stored in a locked file cabinet. In all other cases, your data will only be identifiable by your unique code. Only the director of the laboratory (Dr. Coyle) will have access to a master list that will link your identity to your code.

Because you will be participating in this study and may do so along with other subjects in a small group, we will ask that you do not disclose names of participants in your group or any information that was discussed with other group members outside of the experimental session.

If it becomes necessary for the Institutional Review Board to review the study records, information that can be linked to you will be protected to the extent permitted by law. Your research records will not be released without your consent unless required by law or a court order. The data resulting from your participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate it with you, or with your participation in any study.

If you choose to participate in this study, you may be photographed or video recorded. Any photographs or video recordings will be stored securely and only the research team will have access to the recordings. Recordings will be kept for 3 years after the research experiment has been completed and then erased.

Whom to contact with questions about the study?

Prior, during or after your participation you can contact the researcher **Heath Burton** at **(864)-940-4103** or send an email to **heath.burton@utexas.edu** for any questions or if you feel that you have been harmed.

This study has been reviewed and approved by The University Institutional Review Board and the study number is **2015-11-0074**

Whom to contact with questions concerning your rights as a research participant?

For questions about your rights or any dissatisfaction with any part of this study, you can contact, anonymously if you wish, the Institutional Review Board by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu.

Participation

If you agree to participate please sign and return this form to a member of the research team.

Signature

You have been informed about this study's purpose, procedures, possible benefits and risks, and you have received a copy of this form. You have been given the opportunity to ask questions before you sign, and you have been told that you can ask other questions at any time. You voluntarily agree to participate in this study. By signing this form, you are not waiving any of your legal rights.

Photography and video recording of your sessions is optional. However, if participants agree to be photographed or video recorded their images may also be used for professional and educational presentations not related to this research study.

______ I agree to be **photographed and video recorded.**

______ I do **not** want to be **photographed and video recorded.**

Printed Name

Signature Date

As a representative of this study, I have explained the purpose, procedures, benefits, and the risks involved in this research study.

Print Name of Person obtaining consent

Signature of Person obtaining consent Date

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