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Stride Frequency, Body Fat Percentage, and the Amount of Knee Flexion Affect the Race Time of Male Cross Country Runners

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Summary

Cross country running is a popular sport, requiring high physical effort running on a course of hills and valleys (both uphill and downhill) for 5 kilometers (~3.1 miles) in a group of athletes all competing for the best time. In the area of sports science, both runners and coaches are interested in the characteristics of elite runners. What makes them so fast? In order to determine the attributes of elite runners and identify which physical attributes contributed to race performance, we invited male cross country runners participating in the Iowa high school 2013 state cross country meet to the Exercise Physiology Laboratory at the University of Northern Iowa to undergo testing. Variation in the runners' attributes appeared to account for roughly 60% of performance differences, with stride frequency being the most important determinant of performance. We performed gait analysis on joint angles in an attempt to explain differences in stride frequency. The downhill running mechanics of each test subject were assessed by film analysis of running form in three distinct positions: flat, 5% decline, and 10% decline. This kinematic study showed that the degree of knee flexion was highly associated with stride frequency. Higher stride frequency in faster runners correlated with a greater knee flexion during the early and late stance stride positions. We hypothesize that greater knee flexion may limit deceleration between each step and provide force during the "push-off" phase of running, improving overall running performance.

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Introduction

Cross country is a popular high school sport for both boys and girls and is offered in every U.S. state. Over 440,000 high school students in the U.S. participate in cross country each year, making it the 6th most popular sport for girls and the 7th most popular for boys (8). Because of the sport's rising popularity, cross country athletes and coaches have shown increasing interest in the characteristics of elite runners. Therefore, the purpose of the study was to determine the physical attributes and run mechanics of high school cross country runners and examine their degree of correlation with the runners' race times.

In previous studies of other sports, elite athletes have been distinguished based on their physical attributes, such as maximum oxygen uptake (VO_2 max), run economy, anaerobic threshold, and anthropometry (height, weight, and body fat) (6). VO_2 max is the maximum rate at which oxygen can be obtained from ambient air and transported to cells for use in cellular respiration during physical activity. Run economy is the steady-state submaximal oxygen uptake at a given running velocity (5); the lower the oxygen consumption at a given submaximal running speed, the better the economy (4).

While elite endurance athletes are distinguished by their VO_2max scores, the ability to sustain a high percentage of VO_2max is perhaps even more predictive of endurance performance. This ability is related to the anaerobic threshold. Anaerobic threshold is the point in oxygen consumption during exercise where there is a sharp increase in anaerobic energy production resulting in a significant increase in lactic acid levels in the blood (2). An endurance athlete's anthropometric characteristics, including height, weight, and body fat percentage, also correlate with performance (3).

In addition to an examination of these attributes, gait analysis can be performed to explain the variation in stride frequency. Gait analysis studies the way in which people move from one place to another and is divided into four distinct fields: kinematics, the measurement of movement; kinetics, the study of the forces acting between the foot and the ground; electromyography, the measurement of the electrical activity of the muscle; and engineering mathematics (7). This study focused primarily on kinematics, where recent studies have utilized high-quality videotaping along with kinematic software to map the mechanics of gait, which has proven to be very useful in providing a better understanding of gait and running.

Running is an extremely complex endeavor that involves multiple interactions among bone alignment, joint range, neuromuscular activity, and kinetic forces (1). Gait analysis of runners is currently accomplished

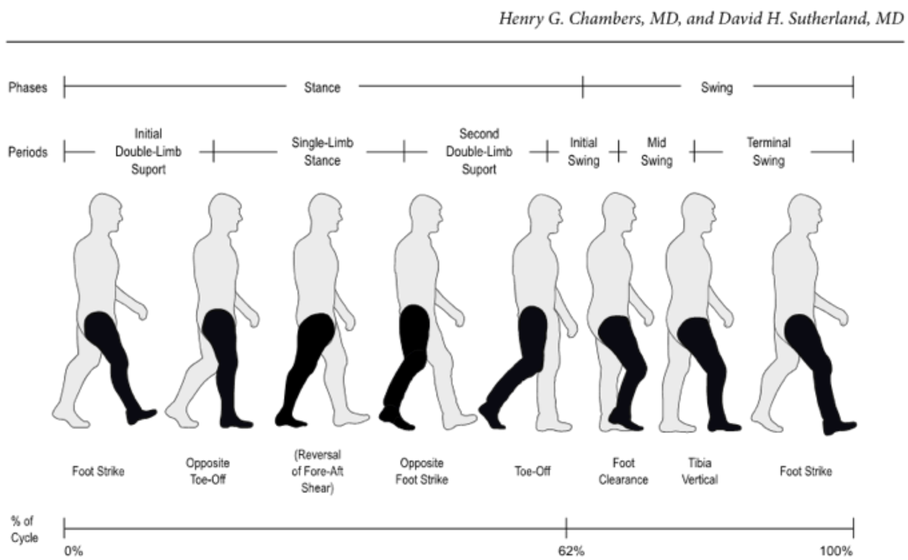

Figure 1: Typical normal gait cycle. Adapted with permission (1).

either by simple observation or by three-dimensional analysis. This type of analysis includes measuring joint angles (kinematics), joint forces (kinetics), muscular activity, foot pressure, and energetics (measurement of energy replaced) (7). A complete gait cycle is defined as movement from one foot strike to another successive foot strike on the same region. This includes both a stance phase and a swing phase, as shown in **Figure 1**. More specifically, the events of the gait cycle are: foot strike (early stance), take off (late stance), float (initial swing), opposite foot mid-stance (mid-swing), and tibia vertical (terminal swing) just prior to the successive foot strike (1).

Physical data was determined using standard laboratory methods in body composition and metabolic testing. Running stride data were collected by filming participants running on a treadmill under various conditions, and gait analysis was performed using kinematics software to analyze the recordings. Statistical analyses consisted of regression analyses and ANOVA.

The results of these experiments provided important insights into the characteristics of elite cross country runners. First, high stride frequency and low body fat percentage accounted for 59% of the variation in the runners' five-kilometer state cross country meet race times. Second, runners with greater knee flexion at the point of contact had faster race times under some conditions. These factors explain much of the variance observed between cross country runners' race times.

Results

A total of twenty participants completed all testing, but one participant was not included in the regression analysis due to equipment malfunction. The rank order, individual state race times, and physical attributes of each subject can be found in **Table 1**.

The results of the stepwise regression analyses found that only stride frequency and percentage body fat were included as predictors with the state race times in a statistically significant manner ($F = 11.319$, df 2, 16, $p = 0.001$). The model summary indicates that strides frequency was the best predictor explaining 37.6% of the variance while adding percentage body fat, the R-squared increased to 58.6%. In general, the higher the stride frequency, the better the race performance (using the group comparisons). In addition, the lower the body fat percentage, the faster the race times. However, these two factors explained only 59% of the difference in performance, suggesting that other factors not measured in this study also contribute to endurance running. The results of the correlational analyses indicated that although maximal oxygen consumption did not contribute to race performance, it did strongly relate to stride frequency, suggesting that the athlete needs a high level of fitness to maintain a high rate of strides over

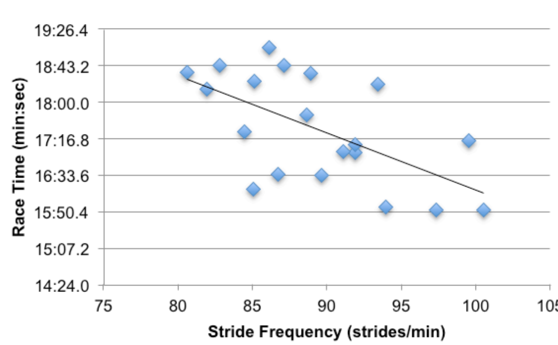

Figure 2: Relationship between stride frequency and race time (r = 0.597).

Rank Order	State Race Time (min:sec)	Cost (mL/kg/m)	VO_2max (mL/min/kg)	%max	Strides/min	Stride Length (m)	Lean Mass (kg)	%fat
1	15:52.5	0.194	59.41	78.6	97.3	2.48	57.00	8.2
2	15:52.6	0.182	49.35	88.9	100.5	2.40	50.64	10.2
3	15:56.1	0.213	59.19	86.8	93.9	2.57	56.68	6.9
4	16:17.4	0.227	63.74	85.7	85.0	2.84	62.54	10
5	16:33.6	0.193	60.62	76.7	89.6	2.69	67.73	9.8
6	16:34.8	0.238	67.66	84.9	86.7	2.78	58.64	7.9
7	17:00.7	0.237	69.67	82.1	91.9	2.63	60.45	6.9
8	17:01.6	0.205	56.03	88.2	91.1	2.65	58.14	6.7
9	17:10.6	0.228	63.91	85.8	91.9	2.63	48.36	13.8
10	17:15.4	0.216	53.23	97.6	99.5	2.42	54.77	12.1
11	17:25.8	-	-	-	84.4	2.86	45.64	13.2
12	17:45.5	0.209	60.02	83.9	88.6	2.72	45.54	13.2
13	18:16.2	0.257	66.95	92.4	81.9	2.95	65.14	8.0
14	18:21.1	0.196	51.86	91.0	93.4	2.58	58.64	12.4
15	18:25.0	0.250	71.71	83.9	85.1	2.84	55.32	12.9
16	18:34.1	0.193	53.10	87.7	88.9	2.72	54.18	8.3
17	18:35.7	0.252	72.59	83.8	80.6	2.99	43.41	13.9
18	18:44.0	0.256	71.72	85.9	87.1	2.77	55.27	15.1
19	18:44.4	0.229	68.47	80.7	82.8	2.92	60.09	13.2
20	19:05.0	0.218	61.17	85.8	86.1	2.80	57.59	13.5
	Mean	**0.221**	**62.13**	**85.8**	**89.3**	**2.71**	**55.79**	**10.8**
	SD	**0.024**	**15.57**	**4.80**	**5.6**	**0.17**	**6.45**	**2.8**

Table 1: Physical attributes of participants.

the duration of the race. The correlational analyses also indicated that the cost of running (run economy) was also strongly related to stride frequency. Therefore, it is expected that runners who choose to run with a higher stride frequency use a larger amount of energy as they perform, and must provide for this energy using the aerobic system (energy provided by using oxygen).

The number of midsole strike runners in each group was similar (4 in fastest group, 3 in middle speed group, 3 in slowest group), with the rest (n = 7) being heel strike runners dispersed among the three groups (2 in fastest group, 2 in middle speed, 3 in slowest group). The one-way ANOVA between groups indicated a significantly (p = 0.023) higher stride rate in the fastest group compared to the slowest group. In addition, stride length was significantly (p = 0.019) shorter in the fastest group as compared to the slowest group. No differences were evident between the middle speed group and either the fastest or the slowest groups with regard to stride frequency or length.

Figures 4–8 illustrate the differences in joint angles between the groups of runners at each phase of the running stride and for each condition. The one-way

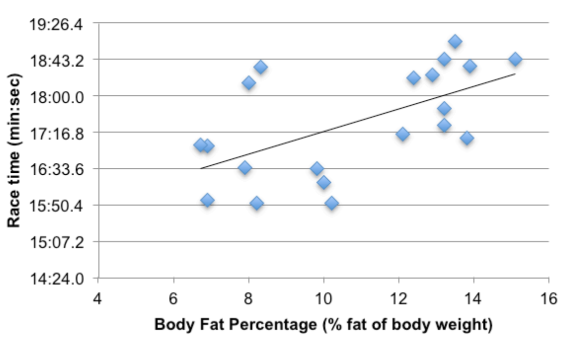

Figure 3: The relationship between body fat percentage and race time (r = 0.586).

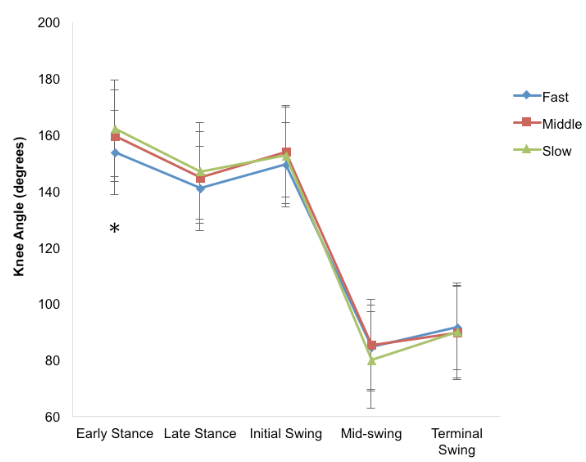

Figure 4: Knee angles between groups of runners across 5 phases of running stride on flat treadmill. "*" denotes that knee angle was significantly smaller in the fast race group, when compared to the slow race group.

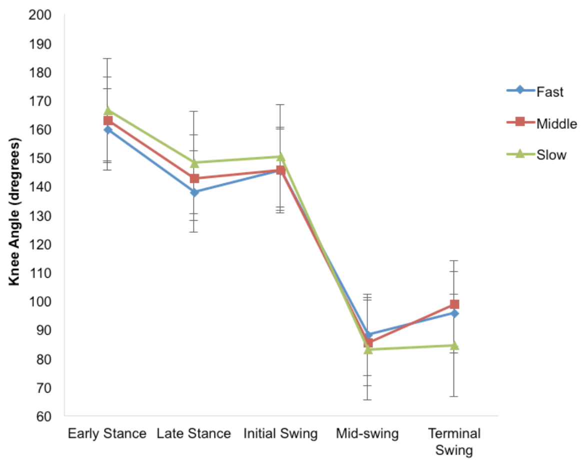

Figure 5: Knee angles between groups of runners across 5 phases of running stride on 5% decline.

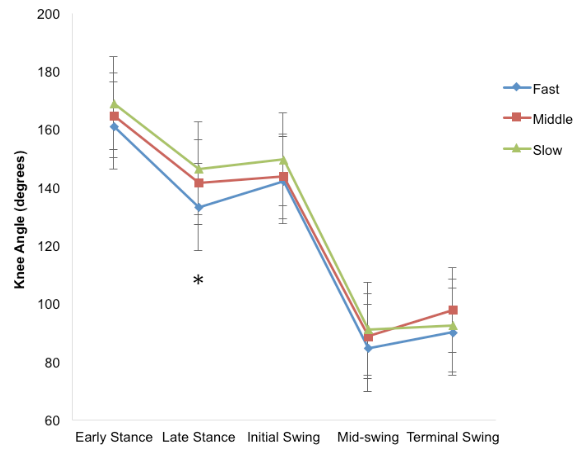

Figure 6: Knee angles between groups of runners across 5 phases of running stride on 10% decline. "*" denotes that the knee angle was significantly smaller in the fast race group than in the middle and slow race groups.

ANOVA of joint angles across groups at each stride position and condition indicated knee differences; however, no significant differences were evident in the hip or ankle joints. For the early stance, during the flat treadmill condition, knee angles indicated more flexion in the fast group vs. the slowest group ($p = 0.012$) (**Figure 4**). In the late stance position, more knee flexion was evident in the 10% decline for the fastest group vs. the middle speed and slowest group ($p < 0.001$) (**Figure 6**). No other differences were present, although trends were evident in the early stance for the 5% decline and 10% decline. In both cases, the fastest group had smaller knee angles, suggesting more flexion of the knee at the point of foot contact. There was a moderate correlation between knee angle and race time at the early stance ($r = 0.53$, $p = 0.033$), late stance ($r = 0.55$, $p = 0.018$), and terminal swing ($r = 0.47$, $p = 0.049$), with only one other significant correlation. Ankle angle was negatively correlated ($r = -0.516$) with race time during the early stance phase.

Discussion

The purpose of this study was to determine the correlation between the runners' physical attributes and their race performance. We found that higher stride frequency and lower percent body fat explained 59% of the variation in race times. Therefore, there are other factors affecting the other 41% of this variance, which may include mental toughness and race strategy. Our analysis of joint angles may explain the reason that stride frequency and length were different between groups. Although multiple joints were evaluated, the results showed that runners with greater knee flexion at the point of contact had faster race times. These run kinematic data could be used to assist coaches and runners in better understanding what factors help to elevate elite runners.

The height of the runner and lean body mass were not correlated with performance. The heights for these runners ranged from 62 inches to 76 inches; however, the top three runners were shorter than the average height of 68.75 inches. Additionally, the amount of lean body mass, an indicator of skeletal muscle, did not correlate with race performance. Thus, body size and amount of muscle are not factors in predicting performance and do not contribute to endurance performance.

Body fat contributes to body mass (weight carried throughout the race), and it was not expected to be a major contributor to performance for this relatively short race. However, low levels of body fat do contribute to race performance to a certain extent, accounting for about 21% of the variance. Based on the regression model, leaner runners are at an advantage.

With almost 40% of performance differences explained by variation in movement pattern, some further examinations are needed to determine whether running on hills has any effect on stride frequency. All cross country courses have both uphill and downhill portions of the race. For our study, we only examined the run mechanics of the downhill running.

A one-way ANOVA of the joint angles of the hip, knee, and ankle among groups (fast, mid, slow) was performed at each stride position and for all three running conditions. The results indicated differences in the knee joint angles; however, no significant differences in the hip or ankle joints were found (**Figures 7-8**). The fastest group had smaller knee angles, suggesting more flexion of the knee at the point of foot contact. Therefore, this study showed that runners with greater knee flexion

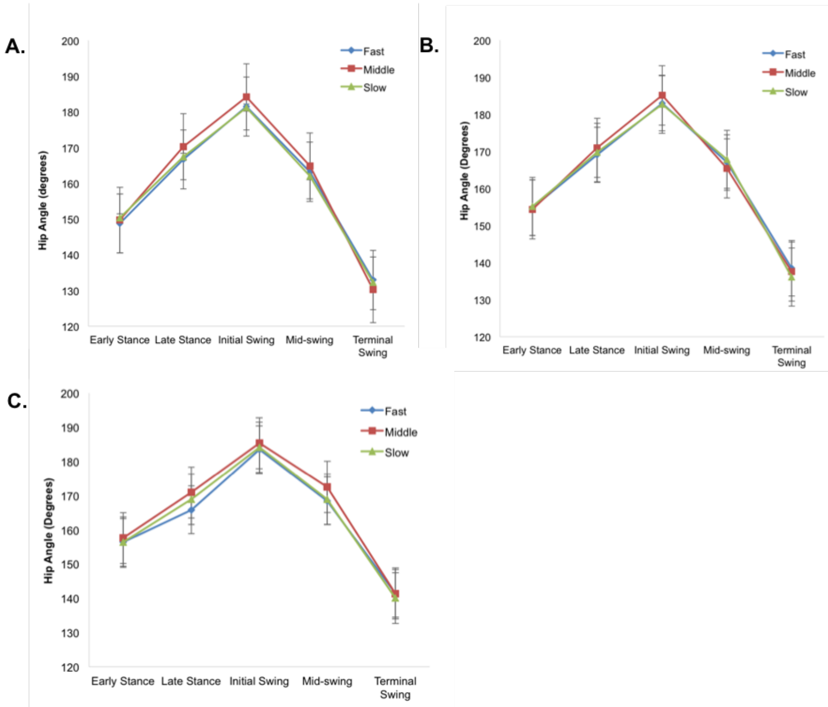

Figure 7: Hip angles between groups of runners across 5 phases of running stride on (A) a flat treadmill, (B) 5% decline, and (C) 10% decline.

at the point of contact generally have better race times.

While care was taken to design this study in the way that best fits the purpose of the research, it still has limitations. For instance, no measures of uphill run mechanics were taken, and the physical performance tests on the treadmill to determine VO_2 were conducted at 9.0 mph, while the average pace of the runners in the state meet ranged from 10.0 mph to 11.0 mph. In addition, run economy was measured only in the flat treadmill position. It is possible that leg power in running hills might explain more of the variance in these data; however, the laboratory did not have the capacity to measure this condition. In the future, a similar experiment could be performed on runners in the field.

For this group of adolescent male athletes, we used the Siri equation to estimate the body fat percentage. This method was used due to the lack of information on maturation levels or ability to determine an appropriate youth adjusted equation from the raw data. However, this equation assumes the subjects are adults (aged 20-50 years), and it is possible some of the athletes had not yet developed into their young adult form (bone density, water content of the body). Other methods of measuring body fat percentage use skinfold thickness (measure of area subcutaneous fat), images of low-density tissue using X-ray, or the impedance of an electrical current (bioelectrical impedance) (9).

Additionally, a study of sprinters' run mechanics could be performed and the results could be compared to those of the cross country runners. This could reveal differences between short-distance and long-distance running.

Another possible future direction could be to look at the effect of upper body joint angles in endurance runners on race times. Common coaching strategies often include directing athletes to use their arms while running, but results of such an experiment could reveal advantageous approaches to this strategy. Also, the majority of the group of subjects tested in this study fell in the category of elite runners, due to the fact that all of them participated in the selective state cross country meet. The experiment could be designed to include more non-elite runners to further make clear the distinguishable characteristics between fast and slow runners.

Finally, repeating the study with female runners would help discover if the same physical characteristics co-vary with race time in both sexes. Results of these experiments should not be generalized and applied to other sports such as basketball and soccer, since the movement patterns for athletes of these sports are multidirectional, not linear as those of cross country runners. More research is required in order to better understand the attributes of elite athletes in these sports.

Methods

Subjects

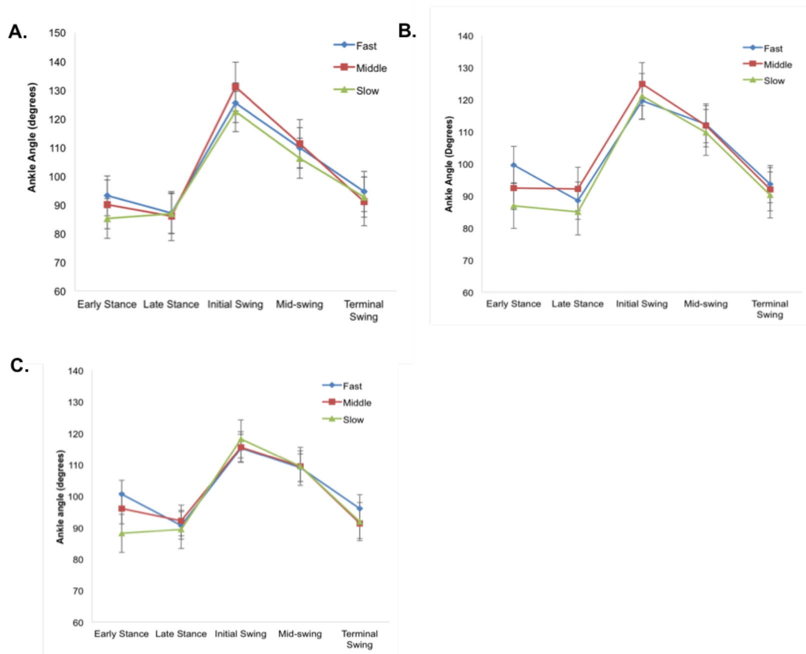

Figure 8: Ankle angles between groups of runners across 5 phases of running stride on (A) a flat treadmill, (B) 5% decline, and (C) 10% decline.

The target group for this study consisted of male cross country runners who participated in the Iowa high school state cross country meet. These athletes were invited to participate in testing to determine the attributes of elite runners and identify which factors contributed most to performance. Three teams in the Cedar Valley area (Cedar Falls High School, Hudson High School, and Denver High School) were selected for invitation, since seven members of the teams had completed the same five-kilometer race course at Fort Dodge and finished with a variety of times. Over a ten-day period within three weeks after the state meet, a total of 20 athletes came to the laboratory for a series of tests. All of the participants were male cross country athletes ranging in age from 15 to 18 years old. Parental consent and subject assent were obtained with knowledge that the runners would not be compensated.

Physical Data Measures

TBody size (height and weight) and body composition (lean mass, %fat) were evaluated using standard laboratory methods. All measurements were taken without shoes with subjects wearing shorts, shirt, and socks. Items in the pockets of the clothing were removed to provide the most accurate weight measurement. Body mass was measured using a digital scale. The subject's height was determined using a portable stadiometer. Using these measures, we calculated body mass index (BMI).

The next physical measure was body composition using a BOD POD air replacement plethysmograph. This device uses air displacement to determine body volume, which allows for calculation of body density (mass over volume). Predictions of body fat percentage and fat-free mass were made using the Siri general population equation.

Physical Performance Testing

In the next phase of the testing, each subject was asked to run on a treadmill while being filmed with a high-definition, high-speed camera. After a warm-up phase, a common speed of 9.0 mph was set, and each athlete ran on a flat, 5% decline, and 10% decline grade for a duration of two minutes at each grade. At the end of each stage, a five-second segment was filmed for use in analysis of contact time, flight time, and point of initial contact (heel vs. midsole). From these measures, stride frequency (steps per minute), stride length (average meters over 12 steps), and stride length-to-height ratio were determined.

In the final stage of testing, participants ran on a treadmill while expired air was collected, and a portable metabolic system calculated the rate of oxygen consumption (VO_2) at a speed of 9.0 mph on a flat level to determine run economy. The cost of running (mL O_2/kg body mass/m) was calculated for comparison between runners, with a low value suggesting good run economy. During the next phase, each subject continued to run at

9.0 mph on an incline (increasing 2% per minute) until fatigue. Finally, a peak value of VO_2 was determined to reflect the maximal rate of oxygen consumption (VO_2 max). The run economy VO_2 was used in conjunction with VO_2max to determine the %VO_2 max for this constant speed.

Using the kinematic software, MaxTRAQ by Innovision Systems, Inc., landmarks on the body were identified and marked manually to determine hip, knee, and ankle joint angles for all frames during the selected stride (that was closest to the average stride length). Frames that coincided with the early stance (first contact of left leg), late stance (left foot push-off), swing1 (hip joint at greatest extension), swing2 (hip joint in neutral position), and swing3 (hip at greatest flexion) were used to record joint angles in each of the five stride positions for each of three conditions of the treadmill (flat, 5% decline, and 10% decline). Subjects were divided into three groups based on race time performance: the fastest times (fast n = 6), the slowest times (slow n = 7), and the rest.

Statistical Analysis

All measurements were entered into a data table along with the runners' race times. Each of the subjects was ranked in order of their race time, with 1 being the fastest time and 20 being the slowest time. For the first part of the study, correlational analyses were performed between all of the variables. Since stride frequency and stride length were highly correlated, both were used for the regression analyses. All of the other variables were entered using a simple stepwise regression. This statistical program identified the variables that contributed to a significant (two tailed) prediction equation.. In addition, analyses of variance (ANOVA) were performed on the stride frequency, stride length, and joint angles between the three groups for each running condition. These analyses were a one-way ANOVA, which was the simplest way to test means from three groups. The grouping of runners who finished with fast, middle, or slow times is commonly done by coaches to evaluate field performances. The differences in race times are not normally distributed, so they were clustered based on how they might place in a state meet. In this case, it was decided to group them based upon this coaching strategy rather than analyses using body size. Finally, correlational analyses were performed on joint angles and race times. All analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 22.

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