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SPEED-RELATED POSITION-TIME PROFILES OF ARM MOTION IN TRAINED WOMEN
DISTANCE RUNNERS

THE UNIVERSITY OF ARIZONA

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SPEED-RELATED POSITION-TIME PROFILES OF
ARM MOTION IN TRAINED WOMEN DISTANCE RUNNERS

by

Lisa Ann Lusby

A Thesis Submitted to the Faculty of the
DEPARTMENT OF PHYSICAL EDUCATION
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

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ABSTRACT

The purpose of this study was to analyze arm position-time histories of eight accomplished women distance runners. The runners were filmed performing at training, race, and full sprint speeds. For each runner, one stride (two steps) was chosen for analysis. Stride cycle data showed that both stride length and stride rate increased with increases in running speed, while support time decreased and flight time remained relatively constant. Arm position data indicated similar general trends for all eight runners for shoulder joint and three dimensional elbow joint angular position-time histories. Range of motion at both shoulder and elbow joints increased with increases in running speed with smaller increases occurring from training to race pace than from race to sprint pace. Maximum out-of-plane forearm and upper arm position was similar at all three running speeds and was not related to hip or shoulder width in these eight runners.

CHAPTER 1

INTRODUCTION

In the past twenty years, biomechanists have become increasingly interested in identifying variables that contribute to improving and optimizing running technique. Research has been primarily focused on sprinting, where technique is crucial for optimal performance. More recently, research centered on distance running has been conducted with the hope of helping coaches and runners improve running performance (e.g., Nelson and Gregor, 1976). Sport scientists have shown that biomechanically there are optimal combinations of stride rate and stride length to achieve different running speeds (Cavanagh, Pollock and Landa, 1977, Dillman, 1975, Nelson and Gregor, 1976). The primary focus has been on the lower extremities; the upper extremities have rarely been the focus of research.

The lack of research on arm motion in running indicates a need for more descriptive analysis of this motion. The intent of this study will be to investigate how arm motion, specifically at the shoulder and elbow joints, varies within runners performing at three different speeds and across runners performing at the same speed. Furthermore, the arm motion, as it relates to stride length and rate will be examined.

Purpose of the Study

The purpose of this study was to analyze arm position-time histories of eight accomplished women distance runners.¹ The runners were filmed performing at slow and medium absolute, steady state speeds, and at a fast, relative, steady state speed. Selected variables were measured from the film for analysis of stride length and rate, arm motion, and relationships between these variables. The study focused on the following question and its component parts:

For one running stride, how do the variables identified below change across the three running speeds for the group of eight runners and what is the variability within the group at each of the three designated speeds?

A. Stride Variables

1. stride length
2. stride rate
3. stride time
4. support time
5. flight time

B. Position-time profiles for shoulder and elbow joint (motion)

1. position as a function of time
 - a. maximum angular positions for flexion and extension
 - b. range of motion at each joint

1. Subject selection criteria to be described later.

2. angle-angle relationships for shoulder and elbow joint angles
3. extent of out-of-plane motion for both forearm and upper arm
4. time at which maximum flexion and extension at the shoulder and elbow joints occurred relative to the points of foot contact and takeoff in the stride.

Scope of the Study

The design of the study incorporated the following delimitations:

1. For each of the three running speeds, the analysis focused on one stride, composed of a left and right step.
2. Only the arm on the side nearest the camera (left arm) was analyzed.
3. The running speed was specified for both the training pace and the race pace but the full sprint speed varied depending on the runner's ability.

Definition of Terms

Arm Cycle -- One complete arm cycle was measured from the arm position starting at the point of left foot touchdown and ending with the arm position at the point just prior to the next left foot touchdown.

Elbow Angle -- The measured angle between the forearm and an extension of a line placed along the longitudinal axis of the upper arm. (maximum extension = 0° , maximum flexion = 180°)

Shoulder Angle -- The sagittal plane angular displacement of the upper arm in relation to a vertical line through the shoulder joint. This angle was expressed as a negative angle when the upper arm was behind the vertical (extension) and a positive angle when the upper arm was in front of the vertical (flexion).

Stride Cycle -- One complete stride consisting of two full steps was defined in relation to the events of foot contact and takeoff. The stride cycle of interest commenced with left foot touchdown ($L\downarrow$), included the points of left foot takeoff ($L\uparrow$), right foot touchdown ($R\downarrow$), right foot takeoff ($R\uparrow$), and concluded with the point just prior to the next left foot touchdown ($L\downarrow$).

CHAPTER 2

REVIEW OF THE LITERATURE

Little has been written describing arm motion in running and the changes, if any, that accompany variation in running speed. What information there is has been published primarily in coaching journals and has not involved film analysis. In coaching journals, only a few reports have dealt directly with arms in running, and the primary purpose of these articles was to describe the arm motion in sprinting (Dyson, 1977; Hopper, 1964). The question remains, what is the pattern of motion of the arms of distance runners and how does this arm motion change at varying speeds?

There does exist a broad research base on the more general topic of "the biomechanics of running." Within this literature, there are several widely accepted conclusions about what occurs in the lower extremity sagittal plane kinematics at increasing running speeds. The general conclusions are that, as speed increases stride length increases and stride rate remains relatively constant (Bates and Haven, 1973; Cavanagh et al., 1977; Dillman, 1975; Hoshikawa, Miyashita and Matsui, 1971; Miller, 1978; Nelson, 1975; Nelson and Gregor, 1976; Saito et al., 1972). However, as running speed reaches maximum, stride rate increases and stride length decreases slightly (Saito et al., 1974). Trained runners normally have longer strides and a lower stride frequency than do untrained or less-trained runner when running at the

same speed (Cavanagh et al., 1977; Dillman, 1975; Nelson and Gregor, 1976). However, it has been indicated that as runners improve their speed (Nelson and Gregor, 1976) or as good and elite distance runners are compared (Cavanagh et al., 1977) the faster runners have somewhat shorter strides. In regard to stride time, it has been reported (Nelson and Gregor, 1976) that when each step is divided into support and flight times, as speed increases support time decreases. Flight time tends to show higher values for medium speeds than for low or maximum speeds.

Unfortunately, none of this literature mentions arm motion in runners. In 1939, Elftman reported on the function of the arms in walking. His general conclusion was that the primary function of the arms was in counteracting the rotation of the body, as a whole, caused by alternating striding of the legs. In a later study on arm motion in walking (Murray, 1967), similar findings were reported on the counterbalancing role of the arms against excessive trunk rotation. It was suggested by Murray that normal arm swing functioned to regulate the amount of vertical excursion of the center of gravity of the entire body. More recently, Hinrichs, Cavanagh and Williams (1981) found that, in running, the arms have a substantial amount of angular momentum around the vertical axis in the opposite direction as the legs and trunk. This results in minimal total body angular momentum about the vertical axis, and again, the counterbalancing role of the arms is apparent. The study, however, did not address the kinematics

of arm motion, or whether or not the counterbalancing role of the arms results in "mirror-image" displacement patterns for the legs.

In a 1964 Track Techniques article by Hopper, several theories were presented about the role of arm motion in sprinting. The theories concerned principles of acceleration and the function of the arms in reducing ground reaction forces. Hopper's theories, although logical and pertinent to understanding kinetic aspects of sprinting, have not been verified by experimental research or film analysis.

In a similar vein, Wickstrom (1977) commented on observations of changes in elbow angle during sprinting. He stated that during the backswing, the elbow first extends and then flexes to a right angle position. This position, according to Wickstrom, is retained on the forward swing. The elbow continues to flex slightly more before the commencement of the backswing.

One other pertinent article was found in Runner's World (1980), a magazine directed to runners and coaches. Most of the information presented was obtained from coaches, however some of the observations were based on research done by Cavanagh and colleagues at the Biomechanics Laboratory of Pennsylvania State University. The coaching opinions mentioned, in regard to arm motion for distance runners, included: 1) for "fluid" arm swing, the arms must be carried low and relaxed, 2) runners should avoid rigid arm carriage, 3) the elbows must swing back in a straight line, moving no more than three to five inches on each side of the body, 4) leg speed, stride length and

"tempo" are all dependent on the upper body strength, and, 5) the movement of the arms in opposition to the legs should be fully utilized. These opinions have yet to be verified through film analysis.

In summary, little information, descriptive or causative, was found regarding arm motion in running. Several theories and opinions have been presented in coaching journals and running magazines, but the majority of these are not quantitatively based. One study, conducted by Hinrichs et al., involved film analysis but was focused kinetically, rather than kinematically. The conclusion of that study was the the arms serve to counterbalance the rotation of the trunk and legs. The lack of research on arm motion in running verified the need for descriptive, position-time profile study involving film analysis.

CHAPTER 3

PROCEDURES

In this section, the subjects are described and the performance conditions and filming procedures are explained. In addition, the data collection and data analysis procedures are presented.

Subjects

Eight successful women distance runners volunteered and provided their informed consent to be subjects in this study. (See Appendix A for content of Subject Consent Form.) All women were competitive, varsity, college runners at distances of 1500 to 10,000 meters. Four of the subjects had been voted All-American distance runners and one holds the Junior South African National record for the 1500 meters. (See Appendix B for subject characteristics.)

Performance Conditions

The runners were filmed while running at three specified speeds on a 400 m regulation track. The speeds were chosen based on training and racing times for these runners. The slow speed was designated as 3.83 ± 0.3 m/s, a pace corresponding to a seven minute mile. This was an average training pace for these runners. Medium speed was defined as 5.5 ± 0.3 m/s, corresponding to a mile race pace of 4:50 minutes or a 3000 m time of 9:05 minutes. The fast pace varied among individuals and was an all-out sprint. As measured from

film, the sprint times actually varied from 6.25 m/s to 8.12 m/s, ($\bar{X} = 6.94 \pm 0.63$ sd), corresponding to 100 meter times from approximately 16 to 12 seconds respectively. In subsequent figures and tables the paces will be referred to as TP for the training pace, RP for the race pace and SP for the full sprint.

Running speed was recorded by photocells set up at the beginning and end of the filming area. The filming area was a seven meter distance marked off on the fourth running lane. In order to pace the runners, markers were set at intervals on the track and a whistle sounded at the time the runner was to be at each marker.

Filming Procedures

Subjects were filmed from a side view using a 16 mm Locam camera set to operate at 150 frames per second. The actual film speed was calculated from 100 Hz timing light markers exposed on the edge of the film by a LED within the camera. The camera was placed 52 m away from and perpendicular to the running path. A zoom lens with a 70 mm setting was used. A 16 mm Bolex camera, operating at 32 fps, filmed the front view of the runners and thus the side to side displacement of the upper extremities. Ektachrome EF film was used in both cameras.

Subject Markings

Subjects were marked using dark tape placed at the level of the joint centers (Figure 1). Markings were at the level of the shoulder joint (approximated by a horizontal line one inch below the

Figure 1. Example of subject markings and illustration of one full stride.

acromion process), elbow and wrist, as well as at the hip joint (at greater trochanter), knee and ankle of the left leg (leg closest to the camera). Measurements of length (or width, where appropriate) were taken of the following segments: shoulder-elbow, elbow-wrist, bi-acromial, greater trochanter-knee, knee-ankle, knee-ground (in running shoes), and bi-trochanter. (See Appendix B for segment measurements.)

Analysis Equipment

A Hewlett-Packard 9810A programmable calculator and a 9865A digitizer were used for digitizing selected lengths and angles. The digitizing platen was 17x17 inches¹ and the film image size to real life size ratio was approximately 10:1. A Cyber main frame computer (Cyber 173) was used in the data smoothing process. A small image Recordak, Model MPE, was used for all film tracings.

Measurements from Film

The conversion factor for distance measurements was calculated from a meterstick filmed in the same plane and at the same distance from the camera as the runner's path. The meterstick was filmed at the start of each runner's three trials. The meterstick length was measured using the digitizer and line length program. The actual one

1. The HP 9865A gives digitized points in English units to the nearest .01 inch (.0254 cm). All references to film coordinates are consequently stated in English units, however metric units are used in all other instances.

meter length was converted to a length in inches which was then divided by the digitized length to obtain a conversion factor indicating that one inch on the film was equivalent to a certain number of inches in real length. Individual conversion factors were calculated for each runner.

For each stride cycle, the following events were identified: time of left foot touchdown ($L\downarrow$), left foot takeoff ($L\uparrow$), right foot touchdown, ($R\downarrow$), right foot takeoff ($R\uparrow$), and subsequent left foot touchdown ($L\downarrow$) (Figure 1). To measure stride length, X-Y coordinates were obtained for the toe of the runner during mid-support of the right and left steps. The differences in the X values were then calculated to determine step length, and the sum of the two step lengths equalled stride length. Stride time was calculated by multiplying the number of frames in the stride by the frame time. One stride contained two full steps and each step was subdivided into support time and flight time. Support time was measured from point of touchdown to the moment of takeoff of the same foot. Flight time was the time from takeoff to subsequent touchdown of the opposite foot. Stride rate was calculated in steps per second by using the reciprocal of stride time. Running speed for the stride selected for analysis was determined by computing the product of stride rate and stride length.

Arm motion data were collected from every film frame (.0067 s intervals) in a given stride. Using a constant origin in every frame, X-Y coordinates for shoulder, elbow, and wrist (Figure 2) were

Figure 2. Points of left foot touchdown, left foot takeoff, right foot touchdown and right foot takeoff including position of shoulder, elbow and wrist at (A) TP, (B) RP, and (C) SP. Arm segment positions shown for every fifth film frame.

collected using the digitizer. These raw data were then smoothed using a second order Butterworth digital filter. The frequency which best fit the raw data was 6 Hz for the X data and 8 Hz for the Y data (Figure 3).

The smoothed data were then used as input to a Hewlett-Packard calculator program which determined the sagittal plane shoulder angle, three-dimensional elbow angle, and the upper arm and forearm segment positions in relation to the side view film plane. The out-of-plane position of the upper arm and forearm segments reflected displacement in the frontal plane. The sagittal plane shoulder angle was expressed in relation to a vertical line hypothetically drawn through the shoulder joint. The true (three dimensional) elbow joint angle was computed by determining the extent of frontal plane position of the upper arm and forearm in each frame based on the ratio of apparent to true length of these segments. (See Appendix C, Part 1, for a description of this application of the Law of Cosines.)

The resultant elbow joint angle graphs showed slight fluctuation from a smoothed curve due to the position of the upper arm and forearm in relationship to the film plane. When either of these segments were less out-of-plane, that is nearer the sagittal plane, a change of .01 ft in the apparent length yielded a change in angle of 8.11° . However, if the segment was well out-of-plane, (i.e., 60°) a change in apparent length of .01 ft yielded a change in angle of less than 1° . Consequently, the elbow angle curve appeared less smooth when the upper arm and forearm were close to the sagittal plane

Figure 3. Comparison of raw vs. smoothed data at 6 Hz for X, 8 Hz for Y.

(Appendix C, Part 2). To evaluate the validity of the three dimensional elbow angle calculations, the three dimensional joint angle position plot was compared to the two dimensional joint angle position plot (Figure 4). This showed that the two graphs coincided when the upper arm and forearm were in or very near the sagittal plane, as verified from careful study of the front view films.²

Analysis of the Data

Data on angular position as a function of time were used to determine points of maximum shoulder and elbow joint flexion and extension as well as to identify angular position at points of foot touchdown and takeoff. Graphs of elbow and shoulder joint angular displacement for the three trials of each runner (Appendices D and E) served as a basis for visual analysis of changes in arm motion with increased running speed.

Angle-angle diagrams, slightly modified from the diagrams described by Cavanagh and Grieve (1973), were used to graphically describe the relationship between shoulder and elbow joint angles. Descriptive statistics (group means and standard deviations) were computed for shoulder and elbow joint angles at each speed at the points of left foot touchdown, left foot takeoff, right foot touchdown, and for the maximum angular positions, range of motion at each joint and time of maximum and minimum out-of-plane positions.

2. The two plots coincided in the region from .335 s to .402 s as indicated by the vertical lines in Figure 4.

Figure 4. Comparison of two dimensional and three dimensional data for elbow joint angle (SP). Vertical lines bound the region where the plots coincide.

Repeatability of Measures
Taken from Film

To determine the repeatability (reliability) of the data taken from the films, all measurements were repeated from one trial of one runner. It was concluded that there was no difference between the repeated and original data for stride and step times, and support and flight times. Stride length was re-measured to within .013 m.

To check precision in digitizing arm position in each film frame, the wrist position in relation to the origin for the same full trial was redigitized. For the original and redigitized trial, the mean (± 1 sd) difference in the raw data values for the 100 film frames was .02 ($\pm .03$) inches for the X coordinates and .03 ($\pm .04$) inches for the Y coordinates. To compare the smoothed data, graphs were made of the two repetitions of the wrist joint X and Y coordinates since this point exhibited greater spacial displacement than did the shoulder and elbow joints (Figure 5). The average difference in the smoothed values for the two repetitions of shoulder, elbow and wrist joint centers was .03($\pm .02$) inches for the X coordinates and .02 $\pm$.01 inches for the Y coordinates.

Since care was taken to operationally define each variable within the stride and to digitize as precisely as possible, and since the variability of the repeated measures was so small, it was concluded that taking one series of measurements for all the trials was sufficient.

Figure 5. Comparison (after smoothing) of the same wrist position-time data digitized two different times.

Summary

Eight successful women distance runners were filmed running at three specified speeds. The speeds corresponded with training, race and full sprint paces for these runners. A 16 mm Locam camera was used and set to operate at 150 fps. The runners were filmed over a seven meter area. They were paced to achieve the slow and medium speeds and verbally encouraged to achieve maximum sprint speed.

For each runner, one stride (two steps) was chosen for analysis. Stride cycle data were subdivided into stride time, stride rate, support time and flight time. Arm position data were collected to determine shoulder joint angle, three dimensional elbow joint angle, and the extent of out-of-plane motion for both upper arm and forearm.

The arm position-time data were presented graphically to determine changes for the runners as a group over the three speeds, and similarities and differences among all runners at each of the three speeds.

CHAPTER 4

RESULTS

In this chapter, the data collected from film analysis are presented. The chapter is divided into two major sections. The first section considers stride length and rate variables. The second section contains the arm position-time profiles including shoulder and elbow angular displacement, maximum shoulder and elbow angular position, range of motion at each joint, angle-angle relationships for shoulder and elbow, and extent of out-of-plane motion of both the forearm and the upper arm.

Stride Length and Rate Variables

Changes in the following variables are presented in this section; stride length, stride rate, stride time (reciprocal of stride rate), support time and flight time. (Appendix D contains stride length and rate data for the individual subject.)

Stride Length and Rate

The group of eight runners was very homogeneous in their stride length and stride rate at each of the three running speeds, as indicated by the small within-group variability seen in Table 1 and Figure 6. For all runners, both stride length and stride rate increased with increases in running speed. It should be recalled that speed of running during the filming session was closely controlled by providing

Table 1. Running speed, stride length, and stride rate.

Pace		Speed (m/s)	Stride Length (m)	Stride Rate (Stride/s)
Training	$\bar{X}$	3.73	2.66	1.41
	sd	.21	.14	.06
Race	$\bar{X}$	5.15	3.38	1.53
	sd	.12	.07	.04
Sprint	$\bar{X}$	6.94	3.71	1.86
	sd	.63	.14	.04

Figure 6. Stride length and stride rate changes with increased running speeds. Horizontal line indicates range of speed at each pace. Vertical line indicates range of variable.

audio signals to pace the runners at the training and race paces. As shown in Table 1 and Figure 6, the variability in speed among the subjects was small at these slower paces, but was larger at the maximum sprinting speed, this latter speed being dependent on the runner's ability. Increased running speed at the race pace over that at the training pace was accomplished primarily by an increase (.72 m) in stride length while stride rate increased (1.2 strides/s) only modestly. At the sprint pace, the mean stride length for the group increased only .33 m over that at the race pace while the increase in stride rate (.33 strides/s) was more than twice the increase in stride rate that had occurred from training to race paces. Despite the greater variation in speed for the sprint condition, the variability in stride length and stride rate was not greater than for the two controlled conditions. This pattern of greater gains in stride length at slow to medium speeds and greater gains in stride rate from medium to fast speeds was characteristic of all eight runners.

Stride Time:

Support and Flight Times

For all three of these variables, their changes with increased running speed were consistent for all eight runners. Stride time, the reciprocal of stride rate, decreased with increases in running speed. The stride analyzed was subdivided into left and right steps, and the absolute time and relative time (percent of stride time) at which foot contact and takeoff occurred were identified (Table 2A and 2B). Step time was further divided into support and flight times. As shown in Table 3 and Figure 7, support and flight were expressed

Table 2. Temporal points of $L\downarrow$, $L\uparrow$, $R\downarrow$, $R\uparrow$, $L\downarrow$ expressed as (A) absolute time and (B) relative time (% of stride time).

Pace		L↓	L↑	R↓	R↑	Total Stride L↓
(A) ABSOLUTE TIME (s)						
Training	$\bar{X}$	0	.2546	.3618	.6131	.7110
	sd		.0172	.0113	.0209	.0228
Race	$\bar{X}$	0	.2002	.3342	.5293	.6516
	sd		.0104	.0181	.0134	.0133
Sprint	$\bar{X}$	0	.1541	.2730	.4271	.5377
	sd		.0190	.0189	.0326	.0379
(B) RELATIVE TIME (PERCENT OF STRIDE TIME)						
Training	$\bar{X}$	0	36	51	86	100
	sd		2.45	1.06	2.72	
Race	$\bar{X}$	0	31	57	81	100
	sd		1.67	3.31	1.41	
Sprint	$\bar{X}$	0	29	51	79	100
	sd		2.19	1.64	2.25	

Table 3. Left and right step support and flight times expressed in absolute time and as a percentage of the total step time.

Pace		Time (s)	Support (s)	%	Flight (s)	%
LEFT STEP						
Training	$\bar{X}$	.3509	.2371	72	.1013	28
	sd	.024	.037	6.84	.027	6.84
Race	$\bar{X}$	.3233	.1977	61	.1256	39
	sd	.012	.009	3.58	.0147	3.58
Sprint	$\bar{X}$	.2680	.1474	55	.1206	45.1
	sd	.020	.018	4.23	.012	4.23
RIGHT STEP						
Training	$\bar{X}$	.3612	.2563	71	.1049	29
	sd	.012	.109	5.34	.021	5.34
Race	$\bar{X}$	.3317	.2027	61	.1474	39
	sd	.009	.012	2.96	.055	2.96
Sprint	$\bar{X}$	.2714	.1533	56	.1188	43
	sd	.022	.016	3.80	.014	3.80

(A.)

(B.)

Figure 7. Support and flight times expressed as (A.) Absolute Time and (B.) Relative Time (% of stride time). (Mean $\pm$ 1 sd)

both as absolute time and as relative time (percent of the total step time). Support time decreased linearly as running speed increased, while flight time increased from training to race pace and then remained almost constant (left step) or decreased slightly (right step) from race to sprint pace. When expressed as percentages of the total step, mean support time for both steps decreased somewhat more from the training to the race pace (71% to 61%) than from the race pace to the sprint pace (61% to 55.5%). Flight time percentage increased in the corresponding manner.

Arm Position-Time Profiles

In this section, the following variables are considered: shoulder and elbow joint angular displacement, maximum shoulder and elbow joint angular position, range of motion of each joint, angle-angle relationships for shoulder and elbow, and extent of out-of-plane motion of both the forearm and upper arm. The data for each variable are presented as group means (± 1 sd) at each running speed while data for the individual subjects are included in Appendix I. The focus for each variable is on changes for the group as a whole as running speed increases. Where pertinent, unique characteristics of individual runners will be discussed either as the subject differs from the others in the group at a particular pace, or as her pattern of change in arm motion across the three running speeds is distinct from the pattern of change of other runners.

Shoulder and Elbow Joint Angular Position-Time Profiles

Figure 8 shows representative shoulder and elbow joint angular position-time graphs for Runner two at each of the three running speeds. (Appendix E contains similar graphs for all runners.)

Important considerations for reviewing the graphs include: the solid, dark line representing elbow joint angle, for which the center horizontal line indicates a 90° angle; the dotted line representing shoulder joint angle, for which the center horizontal line indicates 0° or a vertical upper arm position. Included on each graph are four vertical lines that represent points of $L\downarrow$ (always occurring at the start of the cycle), $L\uparrow$, $R\downarrow$, and $R\uparrow$. For both shoulder and elbow joints, flexion is represented by a positive slope while extension is represented by a negative slope.

General Trends

For all eight runners at all three running speeds, the angular displacement at the shoulder joint was as follows: flexion occurring from $L\downarrow$ to $L\uparrow$, maximum flexion near $L\uparrow$, extension from $L\uparrow$ to $R\downarrow$, maximum extension near $R\downarrow$, and flexion as the cycle repeated itself. Thus, from touchdown to takeoff of the left foot, the left arm was swinging forward. During forward recovery of the left leg and the support period of the right foot, the left arm was swinging backward.

The most common angular displacement pattern at the elbow joint was as follows: a brief period of extension just after $L\downarrow$, followed by flexion; maximum flexion occurring around time of $L\uparrow$,

Figure 8. Shoulder and elbow joint position-time graphs for runner two at each of the three paces.

extension until after $R\downarrow$, followed by flexion until $R\uparrow$ and then extension occurring as the cycle repeated. In other words, elbow flexion occurred as the shoulder joint flexed. Maximum elbow extension occurred as the shoulder extended bringing the upper arm backward to the vertical. As shoulder extension continued and the upper arm approached a position well behind the trunk, the elbow joint again flexed. These general patterns for shoulder and elbow joint angle displacement are discussed more specifically in the subsequent sections of this chapter. In Figure 9 the angular position-time graphs for shoulder and elbow joints are grouped for all three running speeds. Figure 9 illustrates the data for Runner 2 whereas similar graphs for the other runners are included in Appendix F. The pattern of motion at both joints remained the same as running speed increased, but was shifted slightly in time as a result of the stride occurring over a shorter period of time.

In order to look more closely at shoulder and elbow joint angular changes, the joint positions at the clearly identifiable points of $L\downarrow$, $L\uparrow$, $R\downarrow$, and $R\uparrow$ are summarized in Table 4. While the mean values for all eight runners for both shoulder and elbow joint angular position show the same trends over increased running speeds, the larger standard deviations at the sprint pace indicate a greater amount of variability in the group than at the training or race paces. The increased variability at the sprint pace over that at other paces also is evident in Figure 10 A, B and C, which graphically displays the data in Table 4. These Figures show the group mean (± 1 sd) for

(A.)

(B.)

Figure 9. Position-time graphs for (A) shoulder joint and (B) elbow joint of runner two at all three paces.

Table 4. Shoulder (S) and elbow (E) joint angular position (degrees) at points of L↓, L↑, R↓, R↑.

Pace		L↓		L↑		R↓		R↑	
		S	E	S	E	S	E	S	E
Training	$\bar{X}$	-46.0	84.7	-.42	93.4	-8.7	87.0	-55.0	85.6
	sd	6.4	8.3	7.5	7.8	4.2	7.5	2.6	8.0
Race	$\bar{X}$	-45.0	84.4	11.8	101.0	-7.6	79.8	-61.4	85.7
	sd	6.9	9.6	10.6	7.9	10.7	8.8	3.9	6.4
Sprint	$\bar{X}$	-40.8	83.6	32.9	108.9	-1.3	78.2	-73.9	80.6
	sd	9.9	13.3	10.8	16.0	9.8	20.2	5.9	12.0

Figure 10. Shoulder and elbow joint angular position (mean $\pm$ 1 sd) at points of L↓, L↑, R↓, R↑, at (A) TP, (B) RP, and (C) SP.

shoulder and elbow joint angular position at the four points of $L\downarrow$, $L\uparrow$, $R\downarrow$, and $R\uparrow$.

Maximum Shoulder and Elbow Joint Angular Positions

Positions of maximum shoulder and elbow joint flexion and extension (Table 5A), as illustrated in Figure 11, and the time at which they occurred during the stride (Table 5B) are the focus of this section.

In the stride cycle defined as commencing with left foot touchdown, maximum shoulder flexion and maximum elbow flexion in the left arm occurred prior to maximum extension at these two joints. This occurred in the majority of runners at all three paces (Figure 12). At the training pace, maximum shoulder flexion preceded maximum elbow flexion more so than at the faster speeds where the two maxima tended to occur either very close together or simultaneously. In only one runner at one pace (Runner 7, TP) did maximum elbow flexion occur later in the cycle. In relation to the football patterns, maximum shoulder and elbow joint flexion occurred very close to the time of L for all runners at all three paces (Figure 12). At the fastest running speed compared to the slowest running speed, the positions of maximum flexion were greater at both the shoulder joint ($\bar{X} = 34.0^\circ$ vs $\bar{X} = 0.3^\circ$) and at the elbow joint ($\bar{X} = 111.2^\circ$ vs $\bar{X} = 96.5^\circ$) (Table 5A).

Following maximum shoulder and elbow flexion, maximum elbow extension normally occurred, and finally, maximum shoulder extension. These two events did not occur as close together in time as did the

Table 5. Maximum shoulder and elbow joint angular position (A) and the time at which these maxima occurred (B).

(A) POSITIONS AT MAXIMA (DEGREES)					
Pace		○	△	▲	●
Training	$\bar{X}$	.3	96.5	69.8	-55.6
	sd	7.2	7.9	7.3	3.2
Race	$\bar{X}$	12.6	102.4	67.6	-63.7
	sd	10.3	7.0	7.9	3.9
Sprint	$\bar{X}$	34.0	111.2	60.9	-75.9
	sd	11.7	15.9	12.5	7.0

(B) TIME (% OF CYCLE) AT WHICH MAXIMA OCCUR					
Pace		○	△	▲	●
Training	$\bar{X}$	36.0	41.0	59.0	87.0
	sd	4.0	14.2	15.0	3.7
Race	$\bar{X}$	33.0	32.0	47.0	85.0
	sd	2.7	2.6	27.0	3.0
Sprint	$\bar{X}$	30.0	31.0	51.0	82.0
	sd	2.2	4.5	21.0	1.8

KEY: maximum shoulder flexion
maximum elbow flexion
maximum elbow extension
maximum shoulder extension

Figure 11. Definition of shoulder and elbow joint positions at points of maximum flexion and extension.

Key: ○ Maximum shoulder flexion
 △ Maximum elbow flexion
 ▴ Maximum elbow extension
 ● Maximum shoulder extension

Figure 12. Time of maximum shoulder and elbow joint flexion and extension expressed as percent of the total stride.

flexion maxima and were normally separated by a time span of approximately 20% of the cycle (Figure 12). Maximum elbow extension normally occurred between $R\downarrow$ and $R\uparrow$, and maximum shoulder extension occurred very close to the time of $R\uparrow$. As running speed increased, maximum elbow extension tended to occur slightly closer to $R\downarrow$. In four trials, (Runner 7, TP; Runner 2, RP; and Runner 8, RP and SP) maximum elbow extension occurred at the start of the cycle, however the elbow was extending between R and R as can be seen in the position-time graphs for these runners. At the fastest running speed, the average position of maximum shoulder extension was greater than at the slowest running speed ($\bar{X} = -75.6^\circ$ vs $\bar{X} = 55.6^\circ$). The elbow joint was only slightly more extended, on the average, at its point of maximum extension, for the fastest running speed compared to the slowest running speed ($\bar{X} = 60.9^\circ$ vs $\bar{X} = 69.8^\circ$) (Table 5A).

Range of Motion at Shoulder and Elbow Joints

For the group of eight runners, the mean range of motion at the shoulder and elbow joints is presented in Table 6. A smaller increase in shoulder range of motion (20.3°) was noted from training to race pace than from race to sprint pace (31.2°). Likewise, elbow range of motion increased 7.9° from training to race pace and 14.0° from race to sprint pace. As seen in Figure 13 and Table 6, the group standard deviation also increased more from race to sprint pace than from training to race pace. This follows the trend that more variability existed among the runners at the sprint pace, which was

Table 6. Shoulder and elbow joint range of motion.

Pace		Shoulder Range (Degrees)	Elbow Range (Degrees)
Training	$\bar{X}$	55.9	26.7
	sd	6.9	7.5
Race	$\bar{X}$	76.2	34.6
	sd	9.0	9.5
Sprint	$\bar{X}$	107.4	48.6
	sd	14.3	14.1

Figure 13. Shoulder and elbow joint range of motion at three running speeds. Vertical line represents ± 1 sd from the mean.

ability-dependent, than at the controlled training and race paces.

Angle-Angle Relationships

Angle-angle diagrams were used to show the relationship between the shoulder and elbow joint angles and how the relationship changed with increased running speed. Figure 14 illustrates the angle-angle diagram for one runner at the sprint pace. Included in Figure 14 are the points of $L\downarrow$, $L\uparrow$, $R\downarrow$, and $R\uparrow$, identified by the runner figures and markings on the diagram. Also, arrows show the direction of the movement. In order to show changes in angle-angle relationships with increased running speed, subsequent diagrams (e.g., Figure 15 and Appendix G) contain plots for all three trials of one runner on one graph. For purposes of simplification, the graphs do not contain markings to indicate the points of $L\downarrow$, $L\uparrow$, $R\downarrow$, and $R\uparrow$.

The angle-angle diagram (Figure 15) illustrates changes in the range of motion of the elbow joint (vertical axis) and shoulder joint (horizontal axis) over the three running speeds. With increased running speed, the general trend was that both the width and height of the plot increased indicating an increased range of motion at both the shoulder and elbow joints. For the majority of runners, as speed increased from training to sprint pace, maximum shoulder flexion moved the upper arm farther ahead of the vertical, while the elbow joint became increasingly more flexed. Runners 1 and 6 exhibited an increase in shoulder flexion but not in elbow flexion as running speed increased.

Figure 14. Examples of an angle-angle diagram for runner two at SP. Included are temporal points of L↑, L↓, R↑, R↓.

Figure 15. Angle-angle diagrams for runner five at TP, RP, SP.

As the upper arm extended backward past the vertical, the elbow joint became more extended with increased running speed except in Runners 4 and 8. The angle-angle diagrams for Runner 5 (Figure 15) exhibited a general pattern and shape that was characteristic of four of the eight runners. (See Appendix G for angle-angle diagrams for all runners.)

Runners 1, 2, 5 and 6 had the most similar angle-angle patterns at the training pace. Runners 3 and 8 had the smallest range of motion at the elbow joint and their angle-angle diagrams consequently lacked height at the training pace. For both of these runners the training pace diagrams indicated that their elbow joint never flexed as much as 90° . The relationship of the diagram to the vertical line indicating a vertical upper arm position also was pertinent. For four of the eight runners, (Runners 4, 6, 7 and 8), the plot never reached the vertical indicating that their upper arm never flexed in front of the vertical at the training pace.

At the race pace, Runners 3, 4, 5 and 7 had similar patterns. Runner 8 had the most vertically compressed diagram indicating a limited range of motion at the elbow joint. All but Runners 6 and 7 demonstrated shoulder flexion beyond the vertical (0°). For all eight runners maximum shoulder flexion occurred approximately at the time of maximum elbow flexion.

At the sprint pace, Runners 1, 3 and 7 had similar patterns which differed somewhat from the patterns of Runners 2, 4, 5 and 6. Again, Runner 8 had the most distinctively different pattern which

appeared vertically compressed, indicating a limited range of motion at the elbow joint. The plots for all eight runners at the sprint pace crossed both the vertical and 90° lines, indicating maximum shoulder flexion beyond the vertical and maximum elbow flexion beyond 90° . For six of the runners, most of the sprint diagram fell in the lower left quadrant, indicating more shoulder and elbow extension than shoulder and elbow flexion. For Runners 4 and 7, most of the sprint diagram was shifted toward the upper left quadrant indicating greater shoulder extension and elbow flexion. Again, as at the race pace, for all eight runners, maximum shoulder flexion occurred approximately at the time of maximum elbow flexion.

Extent of Out-of-Plane Motion of the Forearm and Upper Arm

Out-of-plane position of the forearm refers to its position relative to the side view film plane, or its displacement in the frontal plane. At the maximum out-of-plane position, the hand typically reached a position approximately in front of the midline of the body while the elbow remained at some distance from the midline of the body. For the upper arm, maximum out-of-plane position refers to frontal plane displacement in which the position of the upper arm was farthest away from the sagittal plane of the body, or toward the side view of camera. In other words, the elbow was farther from the midline of the body than was the shoulder joint. The minimum out-of-plane position for both segments was 0° , or in the sagittal plane (Figure 16).

Figure 16. Example of forearm and upper arm position in-plane (A) and forearm and upper arm position out-of-plane (B).

Focusing on position (degrees), the maximum out-of-plane position of the forearm was very similar (group means within 3°) at all three running speeds (Table 7). The group means for maximum out-of-plane position of the upper arm also were within 3° at all three running speeds. This indicated that the maximum out-of-plane motion for both arm segments during a stride cycle was not dependent on running speed. The standard deviations indicated that there was greater variability among the runners at the race pace than at the training or sprint paces, but the differences were minimal. All runners had a 0° or in-plane forearm position for similar periods of time throughout the stride at all three paces, except for Runner 8 who had similar minimum out-of-plane positions at the training and sprint paces (8.1° vs 8.5°) and twice that amount at the race pace (17.0°). Minimum upper arm position was relatively constant with increased running speed. For two runners the minimum out-of-plane position was 0° indicating that the upper arm was essentially vertical.

Focusing on the time at which these maximum out-of-plane positions occurred, Table 8 shows that mean maximum out-of-plane forearm position occurred approximately midway between L $\uparrow$ and R $\uparrow$ and mean maximum upper arm out-of-plane position occurred around or at the time of R $\uparrow$. Thus maximum forearm out-of-plane position just preceded maximum upper arm out-of-plane position. Minimum out-of-plane positions for both forearm and upper arm typically occurred at varying times during the stride cycle and for varying durations.

Table 7. Maximum and minimum out-of-plane positions for forearm and upper arm.

Pace		FOREARM		UPPER ARM	
		Maximum (DEG)	Minimum (DEG)	Maximum (DEG)	Minimum (DEG)
Training	$\bar{X}$	35.0	1.0	25.0	9.0
	sd	11.3	2.8	7.7	7.4
Race	$\bar{X}$	38.4	2.1	28.6	7.0
	sd	13.6	6.0	11.0	7.9
Sprint	$\bar{X}$	37.4	1.1	25.8	7.6
	sd	9.3	3.0	4.8	7.6

Table 8. Time of maximum forearm and maximum upper arm out-of-plane positions expressed as a percent of total stride time. Included are pts. of L $\uparrow$, R $\downarrow$, R $\uparrow$, also expressed as a percent of stride time.

Pace		Maximum Forearm	Maximum Upper Arm	L $\uparrow$	R $\downarrow$	R $\uparrow$
Training	$\bar{X}$	42	48	36	51	86
	sd	4.9	21.1	2.4	1.1	2.7
Race	$\bar{X}$	40	51	31	57	81
	sd	5.5	24.7	1.7	3.3	1.4
Sprint	$\bar{X}$	44	50	29	51	79
	sd	3.6	20.4	2.2	1.6	2.2

To illustrate more clearly the extent of, and the changes in, out-of-plane arm motion, Figure 17 shows front view tracings of Runner 1 at all three running speeds. (See Appendix H for front view diagrams for all runners.) For Runner 1 at all three paces, maximum forearm out-of-plane position occurred at L $\uparrow$, maximum upper arm out-of-plane position occurred at R $\uparrow$, and minimum forearm out-of-plane position occurred at varying times. Finally, minimum upper arm out-of-plane position occurred at L $\uparrow$ for the training and sprint paces and at R $\uparrow$ for the race pace.

A third pertinent component of out-of-plane position was the joint position when these maxima occurred. Recalling that maximum forearm out-of-plane position generally occurred between L $\uparrow$ and R $\uparrow$, an examination of the position-time graphs revealed that the elbow angle was normally midway between maximum flexion and maximum extension at that time. The shoulder joint was moving from maximum flexion into extension at the time the upper arm was nearing the vertical position. Maximum upper arm out-of-plane position generally occurred very close to R $\uparrow$ and again, referring to the displacement graphs, at R $\uparrow$ the shoulder joint was normally at 0° while the elbow joint was close to maximum extension.

The final consideration of out-of-plane arm motion was its relationship to hip (bi-trochanteric) width and shoulder (biacromial) width. For all eight runners, when hip width was expressed as a percentage of body height, the proportions were very similar (Table 9). The runner with the widest hips in relation to her height was Runner 2,

(A)

(B)

(C)

Figure 17. Front view tracings of runner one at temporal points of L↓, L↑, R↓, R↑, at TP (A), RP (B), and SP (C).

Table 9. Shoulder and hip width expressed as a percentage of total body height.

Runner	Bi-Acromion as % of Total Weight	Bi-Trochanter as % of Total Weight
1	21.5%	17.0%
2	21.6%	19.0%
3	21.6%	18.7%
4	20.9%	18.2%
5	21.7%	18.4%
6	22.3%	18.2%
7	21.5%	18.7%
8	21.3%	17.8%

however her out-of-plane motion was not characteristically different from the other runners. Shoulder width was also very similar across runners when expressed as a percentage of body height (Table 9) and did not appear to be related to the out-of-plane arm motion for these eight runners.

Summary

Both stride length and stride rate increased with increases in running speed. The speed increase from training to race paces was accomplished primarily by an increase in stride length, while stride rate increased only slightly. The increase in speed from race to sprint paces was accomplished by a greater increase in stride rate, while stride length increased only slightly.

The stride was subdivided into left and right steps and step time was divided into support and flight times. Support time decreased linearly with increases in running speed, while flight time increased from training to race pace and then remained relatively constant (left step) or decreased slightly (right step) from race to sprint pace.

Then general trends for shoulder and elbow joint angular position-time histories were similar for all eight runners. The pattern was as follows: the elbow flexed as the shoulder joint flexed; maximum shoulder and elbow flexion occurred simultaneously, and this was followed by maximum elbow extension which occurred as the shoulder extended bringing the upper arm backward to the vertical. Finally, as shoulder extension continued and the upper arm approached a position well behind the trunk, the elbow joint again flexed.

Range of motion at both joints increased with increases in running speed, however a smaller increase occurred from the training to the race pace than from the race to the sprint pace. Angle-angle relationships re-emphasized the changes in range of motion and patterns of shoulder and elbow flexion and extension with increasing speeds.

Maximum out-of-plane forearm and upper arm position was found to be similar (group means within 3°) at all three running speeds. There appeared to be no relationship between hip or shoulder width and the extent of out-of-plane arm motion.

CHAPTER 5

DISCUSSION

The purpose of this section is to relate pertinent findings of this study to the literature which was reviewed. In addition, further implications of the arm position-time data are discussed.

Stride Variables

Stride Length and Stride Rate

The findings of this study corresponded with the findings of those researchers cited in the review of literature. That is, as speed increased from training to race pace, stride length increased and stride rate remained relatively constant. As speed reached maximum, however, the increase in stride rate was twice as great as it was from training to race pace, and length increased only slightly.

Support and Flight Times

As speed increased, for the eight distance runners in this study, support time decreased and flight time remained relatively constant. These findings are in agreement with those of Nelson and Gregor (1976) as mentioned in Chapter 2.

Arm Position-Time Profiles

Although the literature on arm motion in running was scarce, certain results of this study can be related to what has been mentioned in the literature. For example, Wickstrom (1977) commented on changes in elbow angle for the sprint. He stated that during the backswing, the elbow first extends and then flexes to a right angle position. This right angle position is then maintained on the forward swing and finally, the elbow continues to flex before moving into the backswing. An examination of the angle-angle diagram for Runner 5 showed this pattern (Figure 15) but it was not evident for the elbow motion of the remaining seven runners in this study. For all runners, during the backswing, the elbow did first extend and then flex. However, it did not always flex as much as, or maintain, a 90° position. At the training pace, for six of the runners, the 90° elbow position was achieved only briefly during shoulder flexion and for two of the runners the 90° position was never reached.

The article from Runner's World (1980), entitled "Up in Arms," contained some statements by coaches about arm motion and arm carriage in distance runners. One such comment was that, for "fluid" arm swing, the arms must be carried low and relaxed. However, no operational definition was provided for the terms "low" and "relaxed." A review of the front view diagrams for all eight runners showed that the hand position varied considerably throughout the stride and was generally low (below waist level) during foot contact but was above the waist line at take off. The height of the hand and forearm as well

as the range of motion for the shoulder and elbow joints also increased as running speed increased. Another coaching statement was that runners should avoid rigid arm carriage. As shown in the front view diagrams, the "arms" were far from rigid with the range of motion of shoulder and elbow flexion and extension increasing with increased running speed. The amount of lateral or out-of-plane motion of the upper arm and forearm also varied throughout the running stride at all three speeds. A third coaching statement was that the elbows must swing back in a straight line, moving no more than three to five inches on each side of the body. Assuming that "each side of the body" was referring to the displacement of the elbow in front of and behind the vertical, this may hold true for the elbow displacement in front of the body at the training and possibly race paces, but the increased shoulder joint flexion and extension as running speed increases would bring the elbows much farther than three to five inches both in front of and behind the vertical.

Implications of Arm Motion Findings

Reviewing closely the shoulder and elbow angular position-time data, some general trends for changes in arm motion over changes in speed can be seen. As speed changed from a relatively slow training pace to a maximal sprint, the range of both shoulder and elbow flexion and extension increased, however the time at which positions of maximum flexion and extension at these joints occurred in the cycle relative to the events of foot contact and takeoff remained quite constant. This implies that the pattern of motion of the arms,

relative to the stride length and stride rate, remains quite constant regardless of speed, while the range of motion increases as running speed increases.

Another common finding was that there was greater similarity for the runners as a group between the arm motion at the training and race paces than at the full sprint. Again, these two slower paces were closely controlled and the full sprint was not. For these eight trained distance runners, distinct similarities at the training and race paces were found in their angular range of motion and position-time histories of shoulder and elbow flexion and extension, maximum angular position, and time at which the different maximum positions occurred for each cycle. At the sprint pace, however, probably due to the varying abilities of these runners who were not specifically trained at this pace, all of these factors were more variable. The amount of out-of-plane motion which occurred during the stride cycle was the only variable that did not change with increased running speed.

The finding that out-of-plane motion for both the forearm and upper arm remained relatively constant regardless of running speed has several implications. The first is that the arms definitely exhibited motion in the frontal plane and in some cases they did so quite extensively. (See front view diagrams of Runners 4, 5, 7, and 8 in Appendix H.) The concept held by several coaches that the arms should stay in the sagittal plane (Runner's World article) was not shown to be correct for female distance runners running at speeds

ranging from training to sprint pace. The second implication is that the arms of female distance runners may not necessarily move progressively into the sagittal plane as sprinting speed is reached.

The variation of the elbow angular position-time graphs around the horizontal line indicating a 90° position was evidence against another theory (Wickstrom, 1977) that the arms should remain at approximately a 90° angle during running. As mentioned earlier, Runner 8 was the only subject who showed this pattern of a relatively constant 80° elbow angle.

An interesting anecdote is that Runners 6 and 7 are twins. Inspection of their data revealed no greater similarities between these two runners than for any other two runners except for the range of shoulder flexion at the training and race paces. The angle-angle diagrams for Runners 6 and 7 at both the training and race paces showed that the upper arm never passed the vertical position when moving forward. This was not true for any other runners at both paces.

In summary, the factors that were found to change with increased running speed were the range of shoulder and elbow flexion and extension and the time of the cycle or speed of the motion. An implication of the changes in these two variables is that, since angular displacement with respect to time is equal to angular velocity, then as displacement increases and time decreases, angular velocity at these two joints increases with running speed. This is further supported by the increased slopes of the position-time graphs (i.e. Figures 8 and 9) at the race and sprint paces compared to the training

pace. The factors that did not change with speed were the relative timing of the maximum shoulder and elbow flexion and extension in relation to foot contact and takeoff and the range of out-of-plane motion of both the upper arm and forearm.

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER RESEARCH

Summary

Over the past twenty years, the focus of research on the biomechanics of running has been mainly lower extremity kinematics and kinetics. The upper extremity and trunk motion of runners have rarely been analyzed. The need for a position-time analysis of the arms in running was apparent. Since sprinting has been the topic of past research, this study focused on distance runners who are required to perform at varying speeds which include training, racing and sprinting paces. The purpose of the study was to conduct a position-time analysis of the arm motion in trained women distance runners performing at three speeds corresponding to a training pace, a race pace and a full sprint. The variables that were examined were: stride length and rate, angular position-time histories of the shoulder and elbow joints, maximum angular positions at these joints, range of motion of both the shoulder and elbow joint, angle-angle relationships and the extent of out-of-plane arm motion that occurred over the three running speeds.

The literature regarding arm motion in running was sparse. Most of the literature that mentioned arms was in coaching journals and running magazines and consisted of opinions from runners and coaches about how the arms should move during running. These

opinions generally were not supplemented by experimental research or film analysis.

Eight trained women distance runners served as subjects in this study and were filmed running at a training pace, a race pace, and at a full sprint. The films were analyzed to determine changes in stride length, stride rate, and the angular position-time profiles of the shoulder and elbow joint that accompanied increased running speed.

Conclusions

The results of this study can be summarized and categorized as those variables that changed versus those variables that did not change with increased running speed in eight trained women distance runners. The variables that changed with increased running speed included the following:

1. Stride length and stride rate.

Both stride length and rate increased with increases in running speed. Stride length increased more than stride rate as running speed increased from training to race pace, while stride rate increased more than stride length as speed increased from race pace to a full sprint.

2. Stride time; support and flight times.

Stride time decreased with increased running speed. When the time of each step in the stride was divided into support and flight times, support time decreased linearly with increased running speed while flight time increased from training to race pace and then

remained relatively constant (left step) or decreased slightly (right step) as running speed increased from race to sprint pace.

3. Maximum angular positions of shoulder and elbow joints.

Maximum positions of shoulder and elbow joint flexion and extension increased with increases in running speed. This was indicated by an increased range of motion at both joints as speed increased from training pace to a full sprint. The increase was slightly smaller from training to race pace than from race to sprint pace.

4. Speed at which the arm action occurred.

Since stride time was shorter at the faster paces, the time of the arm cycle also decreased with increased running speeds. Thus, the angular velocity of shoulder and elbow joint motion generally increased as running speed increased as deduced from the fact that increased range of motion at these two joints occurred over a shorter time period at the faster running speeds.

The following variables did not change with increased running speeds:

(A) The extent of out-of-plane motion of the forearm and upper arm.

Out-of-plane forearm and upper arm motion was found to be relatively the same at all three running speeds. Also, no relationship between hip or shoulder width and extent of out-of-plane motion was observed.

(B) Relative timing of maximum shoulder and elbow flexion and extension within the stride cycle.

The timing of maximum shoulder and elbow flexion and extension in relationship to the stride footfall patterns remained quite constant at all three running speeds.

Recommendations for Further Research

Since the research on arm motion in runners was very limited, much additional research is needed. For example, there is the need for this same type of study to be conducted using different populations such as male distance runners or sprinters running at slow, medium and fast speeds. Also, a three dimensional kinematic analysis would provide useful information on arm motion in running. A three dimensional study could also include a total body analysis to more thoroughly relate motion of the upper extremities to that of the trunk and lower extremities.

APPENDIX A

SUBJECT CONSENT FORM

Subject Consent FormInvestigator: Lisa Lusby

Project Title: Speed-Related Position-Time Profiles of Arm Motion in Trained Women Distance Runners

This cinematographic analysis is part of a Master's thesis which will study the changes in arm motion over changes in speed in distance running. Permission is requested to film you at three running speeds. The speeds will correspond with a seven minute mile training pace, a 4:50 mile race pace and a full sprint. You will be filmed using a 16 mm Locam camera operating at 150 frames per second. The film will be analyzed to determine what changes occur in arm motion with changes in speed and how arm motion relates to stride characteristics.

Your participation as a subject is voluntary. It will involve approximately one hour of your time. The filming will be done at Rincon Vista track. You are subject to no costs or risks as a result of this study. There are no immediate benefits to you as a participant, however you will be able to view the films of yourself and once the analysis is complete, you will be informed of the results. The benefits of this study are in form of knowledge for the biomechanist, coach and runner. We are requesting permission to use your name, names of races you have participated in and your official times. If you would prefer not to have your name used, you may be referred to by I.D. number. If you wish to cancel your participation, you may do so at any time. The data and films will be used solely for educational and research purposes. Please read the following statements carefully and sign below if you are in agreement.

"The nature, demands and benefits of this study have been thoroughly explained to me. I understand what my participation will involve and that I may withdraw from this study at any time."

"I understand that in the event of physical injury resulting from the filming procedures that financial compensation for the cost of medical care must be born by the subject."

"I understand that this consent form will be filed in an area designated by the Human Subjects Committee with access restricted to the principal investigator or authorized representatives of the particular department. A copy of this consent form is available to me upon request."

Subject's signature: _____ Date: _____

I agree to have my name and times used in this study.

Subject's signature: _____ Date: _____

APPENDIX B

SUBJECT CHARACTERISTICS

Runner's Name	I.D. No.	Age	Ht. (cm)	Wt. (kg)	SEGMENT MEASUREMENTS (cm)							Comments
					Shoulder - Elbow	Elbow - Wrist	Bi- Acromial	Hip - Knee	Knee - Ankle	Knee - Ground	Bi- Trochanter	
Anthea James	1	21	170.2	53.2	25.25	23.00	36.65	44.35	38.85	46.50	29.00	South African Junior National Record Holder-1500 m
Kathy Hildebrand	2	18	166.4	55.5	25.75	21.65	35.95	43.95	36.00	46.85	31.55	
Eliza Carney	3	20	165.1	49.1	26.60	23.10	35.60	42.00	36.60	47.00	30.95	
Gretchen Gwelich	4	20	172.0	55.0	29.20	23.80	36.00	43.80	36.25	47.35	31.30	
Marjorie Kaput	5	23	163.8	49.5	24.55	22.45	35.55	41.00	37.50	46.30	30.20	All-American - Cross Country 1980, 1981 All-American - Indoor Track 1981
Debbie Vetter	6	26	165.1	50.0	27.50	23.10	36.90	41.50	36.65	47.15	30.10	All-American - 800, 1500, 2 mi. Relay, 1977 All-American - 800, 2 mi Relay, 1978 National 1500 m Champion, 1978 National AAU Senior Indoor - 800 m, 1979 All American - Cross Country 800 m, 1978, 1979
Diane Vetter	7	26	160.6	48.2	27.10	22.85	34.60	41.10	37.00	46.20	30.00	All-American - 2 mi. Relay 1977, 1978, 1980 All-American Indoor National Medley, 1980
Bridgette Seip	8	24	182.9	65.9	28.35	25.90	39.05	49.10	44.10	57.00	32.55	All-American - Cross Country 1976

APPENDIX C

CALCULATION OF THREE DIMENSIONAL ELBOW ANGLE AND FRONTAL PLANE POSITION OF UPPER ARM AND FOREARM

PART I. EXAMPLE OF LAW OF COSINES USED TO EXTRACT THREE DIMENSIONAL ELBOW ANGLE FROM FILM

Law of Cosines:

$$\theta = \arccos \frac{\text{apparent}}{\text{true}}$$

Axis Arrangement:

Direction of
Runner's Progression

If (side view) film coordinates are:

Original (True) Segment Lengths:

shoulder-elbow (upper arm) = 10"
elbow-wrist (forearm) = 10"

Upper arm true length = 10"

$$\text{Apparent Length} = \sqrt{(5-0)^2 + (-6-0)^2} = \sqrt{25+36} = \sqrt{61} = 7.81"$$

$$\theta_{\text{UA}} = \arccos \frac{7.81}{10.0} = 38.65^\circ \text{ in frontal plane}$$

Forearm true length - 10"

$$\text{Apparent Length} = \sqrt{(10-5)^2 + (-4-(-6))} = \sqrt{25+24} = \sqrt{49} = 5.385"$$

$$\theta_{\text{FA}} = \arccos \frac{5.385}{10.0} = 57.42^\circ \text{ in frontal plane}$$

To determine elbow joint coordinates with respect to shoulder:

$$\theta_{UA} = 38.65^\circ$$

$$\sin \frac{x}{10} = \frac{\text{opp}}{\text{hyp}}$$

$$x = 10(.6246)$$

$$x = 6.246$$

Elbow True Coordinates = (6.25, 5.0, -6.0)

To determine wrist joint coordinates with respect to elbow:

$$\sin = \frac{x}{10}$$

$$x = 10(.8426)$$

$$x = 8.426 \text{ (in negative x direction)}$$

$$x = -8.426$$

Wrist True Coordinates
with respect to Elbow = (8.426, 5, 2)

Wrist Coordinates with
respect to the Shoulder = (-2.18, 10.0, -4.0)

Elbow Angle given coordinates of:

$$\begin{aligned} \text{shoulder} &= (0, 0, 0) \\ \text{elbow} &= (6.25, 5.0, -6.0) \\ \text{wrist} &= (-2.18, 10.0, -4.0) \end{aligned}$$

$$3\text{-D arc cos } \theta_E = \frac{AB^2 + BC^2 - AC^2}{2(AB)(BC)} = 66.7^\circ$$

If 2-D coordinates had been used:

$$\begin{aligned} \text{shoulder} &= (0, 0) \\ \text{elbow} &= (5, -6) \\ \text{wrist} &= (10, -4) \end{aligned}$$

$$2\text{-D arc cos } \theta_E = \frac{AB^2 + BC^2 - AC^2}{2(AB)(BC)} = 108^\circ$$

PART II. EFFECT OF A SMALL CHANGE IN APPARENT SEGMENT LENGTH ON THE CHANGE IN SEGMENT ANGLE TO THE FILM PLANE.

- l True length of a segment
- s Apparent length of a segment
- θ Angle of the segment with respect to the photographic plane

$$\theta = \text{Arc cos } \frac{s}{l}$$

(Figure from Miller and Nelson, 1976, p. 149).

If the true length = 1.0 ft. (12" which is an approximate length of a forearm or upper arm segment)

For an apparent segment length of .99 ft. $\text{arc cos } \frac{\text{apparent}}{\text{true}} = 8.11^\circ$

$$.90 \text{ ft.} = 25.84^\circ$$

$$.50 \text{ ft.} = 60.00^\circ$$

$$.49 \text{ ft.} = 60.66^\circ$$

$$.40 \text{ ft.} = 66.42^\circ$$

A change of .01 ft. in the apparent segment length yields a degree change of 8.11° when the segment is almost in plane (.99 ft. vs 1.0 ft.) BUT yields a degree change of only $.67^\circ$ when the segment is further out of plane (.49 ft. vs .50 ft. apparent length, or approximately 60° out of plane).

Even if the change is .10 ft. (.40 vs .50 ft. apparent length), the degree change (66.4° vs 60°) is less than the degree change (8.11°) caused by a change 1/10th of this size in apparent length when the segment is nearly in plane (.40 to .50 = .10 ft. with a 6.4° change vs .99 to 1.00 = .01 ft. with an 8.11° change).

APPENDIX D

STRIDE LENGTH AND RATE DATA FOR ALL EIGHT RUNNERS

1

Table D-1. Stride Length Data for All Eight Runners - Training Pace.

RUNNER #	LEFT STEP					RIGHT STEP				
	Step Time(s)	Support(s)	%	Flight(s)	%	Time(s)	Support(s)	%	Flight(s)	%
1	.3685	.2613	70.9	.1072	29.1	.3819	.2747	71.9	.1072	28.1
2	.2948	.2546	86.4	.0402	13.6	.3502	.2747	78.4	.0755	21.6
3	.3618	.2546	70.4	.1072	29.6	.3484	.2546	73.0	.0938	27.0
4	.3685	.2747	74.5	.0938	25.5	.3551	.2613	73.6	.0938	26.4
5	.3551	.2278	64.1	.1273	35.9	.3551	.2278	64.1	.1273	35.9
6	.3551	.2345	66.8	.1206	33.2	.3752	.2345	62.5	.1407	37.5
7	.3484	.2345	67.3	.1139	32.7	.3551	.2479	69.8	.1072	30.2
8	.3551	.2546	71.7	.1005	28.3	.3685	.2747	74.5	.0938	25.5
$\bar{X}$	.3509	.2371	71.5	.1013	28.5	.3612	.2563	70.9	.1049	29.1
SD	.024	.037	6.84	.027	6.84	.012	.019	5.34	.021	5.34

Table D-2. Stride Length Data for All Eight Runners - Race Pace.

RUNNER #	LEFT STEP					RIGHT STEP				
	Step Time(s)	Support(s)	%	Flight(s)	%	Step Time(s)	Support(s)	%	Flight(s)	%
1	.3350	.2077	62.0	.1273	38.0	.3350	.2077	62.0	.1273	38.0
2	.3082	.2077	67.4	.1005	32.6	.3283	.2144	65.3	.1139	34.7
3	.3283	.2010	61.2	.1273	38.7	.3283	.2010	61.2	.1273	38.7
4	.3149	.2010	63.8	.1139	36.2	.3484	.2144	61.5	.1340	38.5
5	.3283	.1876	57.1	.1407	42.9	.3216	.1809	56.2	.1407	43.8
6	.3417	.1943	56.8	.1474	43.2	.3350	.1945	58.0	.1407	42.0
7	.3082	.1809	58.7	.1273	41.3	.3216	.1943	60.4	.1273	39.6
8	.3216	.2010	62.5	.1206	37.5	.3350	.2144	64.0	.1206	36.0
$\bar{x}$	.3233	.1977	61.2	.1256	38.8	.3317	.2027	61.1	.1290	38.9
SD	.012	.009	3.58	.0147	3.58	.009	.012	2.96	.007	2.96

Table D-3. Stride Length Data for All Eight Runners - Sprint Pace.

RUNNER #	LEFT STEP					RIGHT STEP				
	Step Time(s)	Support(s)	%	Flight(s)	%	Step Time(s)	Support(s)	%	Flight(s)	%
1	.2613	.1541	58.9	.1072	41.1	.2814	.1541	54.8	.1273	45.2
2	.2546	.1541	60.5	.1005	39.5	.2479	.1541	62.2	.0938	37.8
3	.2814	.1474	52.4	.1340	47.6	.2546	.1541	60.7	.1005	39.3
4	.2948	.1608	54.5	.1340	45.5	.2881	.1675	58.1	.1206	41.9
5	.2613	.1407	53.8	.1206	46.2	.2680	.1474	55.0	.1206	45.0
6	.2479	.1206	48.6	.1273	51.4	.2613	.1340	51.3	.1273	48.7
7	.2479	.1273	57.3	.1206	48.7	.2546	.1340	52.6	.1206	47.4
8	.2948	.1742	59.1	.1206	40.9	.3149	.1809	57.4	.1340	42.6
$\bar{X}$	.2680	.1474	54.9	.1206	45.1	.2714	.1535	56.5	.1188	43.5
SD	.020	.018	4.23	.012	4.23	.022	.016	3.80	.014	3.80

Table D-4. Rate Data for All Eight Runners - Training Pace.

RUNNER #	Speed (m/s)	=	Stride Length (m)	x	Stride Rate (strides/s)
1	3.73		2.80		1.33
2	4.01		2.59		1.55
3	3.59		2.55		1.41
4	3.34		2.42		1.38
5	3.65		2.60		1.41
6	3.82		2.79		1.37
7	3.89		2.74		1.42
8	3.81		2.76		1.38
$\bar{X}$	3.73		2.66		1.41
SD	0.21		0.14		0.06

Table D-5. Rate Data for All Eight Runners - Race Pace.

RUNNER #	Speed(m/s)	=	Stride Length(m)	x	Stride Rate (strides/s)
1	5.13		3.44		1.49
2	5.13		3.26		1.57
3	5.12		3.36		1.52
4	5.04		3.34		1.51
5	5.27		3.43		1.54
6	4.97		3.37		1.48
7	5.27		3.32		1.59
8	5.30		3.48		1.52
$\bar{X}$	5.15		3.38		1.53
SD	0.12		0.07		0.04

Table D-6. Rate Data for All Eight Runners - Sprint pace.

RUNNER #	Speed(m/s)	=	Stride Length(m)	x	Stride Rate (strides/s)
1	7.04		3.82		1.84
2	7.12		3.58		1.99
3	6.70		3.59		1.86
4	6.17		3.60		1.72
5	7.18		3.80		1.89
6	7.32		3.73		1.96
7	7.97		4.00		1.99
8	6.04		3.68		1.64
$\bar{X}$	6.94		3.71		1.86
SD	0.63		0.14		0.04

APPENDIX E

SHOULDER AND ELBOW JOINT POSITION-TIME GRAPHS
FOR ALL EIGHT RUNNERS AT EACH OF THREE PACES

RUNNER 1

RUNNER 2

RUNNER 3

RUNNER 4

RUNNER 5

RUNNER 6

RUNNER 7

RUNNER 8

APPENDIX F

POSITION-TIME GRAPHS FOR SHOULDER JOINT AND
ELBOW JOINT OF ALL EIGHT RUNNERS AT THE THREE PACES

RUNNER 1

RUNNER 2

RUNNER 3

RUNNER 4

RUNNER 5

RUNNER 6

RUNNER 7

RUNNER 8

APPENDIX G

ANGLE-ANGLE DIAGRAMS FOR ALL EIGHT RUNNERS

RUNNER 1

RUNNER 2

RUNNER 3

RUNNER 4

RUNNER 6

RUNNER 7

RUNNER 8

APPENDIX H

FRONT VIEW DIAGRAMS FOR ALL EIGHT RUNNERS

RUNNER 1

L ↓

L ↑

R ↓

R ↑

RUNNER 2

L ↓

L ↑

R ↓

R ↑

No Front View Diagram For SP

RUNNER 3

RUNNER 4

RUNNER 5

RUNNER 6

RUNNER 7

RUNNER 8

APPENDIX I

ARM POSITION AND RANGE OF MOTION
DATA FOR ALL EIGHT RUNNERS

Table I-1. Shoulder (S) and Elbow (E) Angular Position (Degrees) at Points of Left Foot Touchdown (L↓) Left Foot Takeoff (L↑), Right Foot Touchdown (R↓) and Right Foot Takeoff (R↑).

RUNNER	L↓		L↑		R↓		R↑		
	S	E	S	E	S	E	S	E	
TRAINING	1	-40.4	82.2	7.9	94.9	- 3.4	91.4	-52.8	85.3
	2	-47.0	91.2	1.6	104.3	- 9.9	98.6	-56.3	95.0
	3	-39.9	73.2	10.3	82.3	- 2.0	79.3	-53.0	79.8
	4	-52.8	89.7	- 9.4	90.8	-11.3	80.0	-57.0	80.1
	5	-36.8	78.2	4.2	93.7	- 9.3	82.7	-57.3	82.8
	6	-53.4	86.0	- 9.1	92.0	-15.2	87.0	-59.7	80.6
	7	-52.0	98.7	- 4.2	103.6	- 8.5	95.9	-54.7	100.8
	8	-45.6	78.7	- 4.7	85.4	-10.3	80.8	-54.5	80.3
RACE	1	-35.3	75.2	21.4	94.9	2.1	81.2	-58.9	82.7
	2	-45.3	74.2	10.4	112.3	-24.5	79.4	-65.6	93.4
	3	-44.3	85.9	28.9	104.5	7.1	69.7	-59.7	81.3
	4	-47.8	85.0	8.3	105.9	- 9.1	86.6	-68.6	87.2
	5	-34.0	84.2	16.6	102.7	- 8.5	69.0	-57.8	82.3
	6	-57.3	81.1	- 1.5	88.4	-20.3	75.5	-60.0	78.3
	7	-52.5	106.4	- 1.8	105.5	- 6.2	95.6	-58.2	97.1
	8	-49.2	78.1	11.9	93.9	- 1.3	81.2	-62.8	83.7
SPRINT	1	-36.4	79.2	33.4	84.9	4.5	47.4	-65.0	71.2
	2	-46.0	88.7	31.5	121.0	- 5.6	86.9	-82.9	96.2
	3	-35.4	89.4	51.6	109.2	12.5	55.1	-72.6	69.5
	4	-50.9	97.1	25.1	133.5	-17.14	98.0	-79.5	92.4
	5	-22.9	66.3	39.6	113.3	2.29	70.5	-67.4	73.1
	6	-35.4	68.8	19.8	90.9	-10.01	50.0	-72.6	68.0
	7	-48.0	103.5	40.3	116.4	7.41	92.6	-78.2	94.9
	8	-57.3	76.0	21.6	102.2	- 4.5	85.2	-71.8	79.7

Table I-2. Positions of Maximum Shoulder and Elbow Flexion and Extension (Degrees) and the Relative Time (Percent of Stride Time) at which these Positions Occurred.

RUNNER	SHOULDER				ELBOW				
	Maximim Shoulder Flexion	Time(%)	Maximum Shoulder Extension	Time(%)	Maximim Elbow Flexion	Time(%)	Maximum Elbow Extension	Time(%)	
TRAINING	1	8.5	32	-52.8	86	95.7	40	64.1	63
	2	2.1	36	-57.0	87	105.4	40	78.6	63
	3	10.3	36	-54.0	91	87.4	41	61.1	66
	4	- 8.0	44	-52.9	92	95.5	35	62.7	64
	5	4.7	31	-57.7	84	99.1	26	65.7	62
	6	- 8.4	36	-62.1	87	93.9	38	71.9	63
	7	- 3.3	39	-55.6	90	108.8	74	79.0	23
	8	- 3.9	38	-53.0	81	86.1	34	75.5	66
RACE	1	21.6	33	-60.4	84	96.9	37	60.5	61
	2	10.6	32	-66.8	86	112.3	32	74.9	6
	3	29.7	33	-61.5	85	105.8	34	61.3	56
	4	8.3	31	-70.9	84	105.9	31	66.4	62
	5	16.6	28	-58.5	78	103.1	28	58.0	61
	6	0	32	-64.5	87	92.7	32	65.1	63
	7	- .4	35	-64.1	88	107.4	33	76.7	64
	8	14.1	37	-63.0	84	94.4	31	78.1	1
SPRINT	1	34.1	31	-66.9	80	88.5	25	46.6	50
	2	31.5	32	-82.9	83	123.2	36	68.3	63
	3	52.8	31	-72.9	84	110.8	34	49.0	57
	4	25.5	31	-81.2	82	136.3	35	67.7	62
	5	39.6	28	-67.6	80	117.9	33	56.2	61
	6	20.2	26	-74.1	80	93.4	29	49.1	53
	7	46.6	32	-85.5	84	116.8	24	74.4	61
	8	21.8	32	-72.8	81	102.2	31	76.0	1

Table I-3. Range of Motion (Degrees).

Runner	Pace	Shoulder Range	Elbow Range
1	TP	61.3	31.6
	RP	82.0	36.4
	SP	101.0	41.8
2	TP	59.0	26.9
	RP	77.4	36.4
	SP	98.5	41.9
3	TP	64.3	26.3
	RP	91.2	44.6
	SP	125.7	61.8
4	TP	44.9	32.8
	RP	79.1	39.5
	SP	106.8	68.7
5	TP	62.4	33.4
	RP	75.0	45.1
	SP	107.1	61.7
6	TP	53.7	22.0
	RP	64.5	27.6
	SP	93.3	44.2
7	TP	52.4	29.8
	RP	63.6	30.7
	SP	132.7	42.4
8	TP	49.1	10.6
	RP	77.2	16.4
	SP	94.6	26.2

Table I-4. Maximum and Minimum Out-of-Plane Position (Degrees)

Runner	Pace	UPPER ARM		FOREARM	
		Maximum	Minimum	Maximum	Minimum
1	TP	31.6	10.4	42.6	0
	RP	26.3	13.6	39.9	0
	SP	30.7	16.0	30.5	0
2	TP	30.1	16.9	36.5	0
	RP	37.9	15.9	49.9	0
	SP	31.1	13.3	40.1	0
3	TP	17.7	0	55.2	0
	RP	23.2	0	53.1	0
	SP	24.2	0	55.8	0
4	TP	39.3	18.4	25.0	0
	RP	24.5	17.8	35.1	0
	SP	30.9	14.5	40.0	0
5	TP	23.1	0	40.2	0
	RP	19.9	0	45.5	0
	SP	18.4	0	37.4	0
6	TP	20.5	12.3	19.0	0
	RP	51.8	9.2	9.6	0
	SP	20.6	0	24.8	0
7	TP	23.6	12.0	32.1	0
	RP	25.8	0	42.2	0
	SP	25.8	12.4	39.9	0
8	TP	17.1	1.8	29.6	8.1
	RP	19.3	0	31.7	16.9
	SP	25.0	0	30.9	8.5

Table I-5. Relative Time (Percent of Stride Time) for Maximum and Minimum Out-of-Plane Arm Position and for Temporal Points of L↓, L↑, R↓, R↑.*

Runner	Pace	L↓	R↓	R↑	FOREARM		UPPER ARM	
					Maximum	Minimum	Maximum	Minimum
1	TP	36	51	86	36	0-14, 63-100	57	1
	RP	31	50	82	39	0-3, 75-100	59	78
	SP	29	49	77	40	0-9, 49-74, 94-100	50	1
2	TP	38	51	90	39	0-12, 75-95	39	100
	RP	33	59	83	35	0-6, 88-100, 63-88	24	1
	SP	32	52	83	49	63-88	51	1
3	TP	37	52	88	42	0-9, 67-100	65	
	RP	32	51	82	43	0-9, 59-77, 87-92	32	0-24, 42-56, 78-88
	SP	29	54	82	45	79-66	69	27-56, 79-96
4	TP	39	52	88	39	61-87	35	92
	RP	31	48	81	44	76-86	28	77
	SP	29	51	80	42	59-66, 82-91	41	81
5	TP	32	50	83	41	0-14, 62-100	64	35-42
	RP	29	51	79	46	0-9, 61-100	100	17-50
	SP	28	51	78	48	0-2, 57-100	67	10-57
6	TP	33	49	82	49	0-28, 57-85	5	49
	RP	28	50	80	30	0-27, 42-91, 98-100	49	78
	SP	25	50	78	42	0-13, 20-32, 49-88, 98-100	5	37-39, 42-45, 82-83

Table I-5--Continued

Runner	Pace	L†	R†	R†	FOREARM		UPPER ARM	
					Maximum	Minimum	Maximum	Minimum
7	TP	34	50	86	50	0-27, 61-67, 79-85	68	32
	RP	30	50	81	45	0-23, 64-100	64	35-41
	SP	27	51	77	48	61-73	60	28
8	TP	36	50	88	41	68	56	7
	RP	32	50	83	40	15	56	15-18, 22-37
	SP	31	49	79	41	7	57	17-42

* L† - The start of the cycle, always occurs at 0%.

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