KIN 335 Biomechanics

Lab #3 — Kinematics of Running

Reading Assignment: Enoka, Roger M. (1994). *Neuromechanical Basis of Kinesiology*. Champaign, IL: Human Kinetics, pp. 14-19 (attached).

Introduction: In running events, a competitive athlete's goal is to cover a given distance in the shortest possible time. **From a biomechanics perspective, the goal is to cover the distance with the highest possible average speed.** This is a simple example of how our fundamental principles of linear and angular kinematics become very useful in our understanding of performance. By describing various kinematic aspects of running we can gain some information about strengths and weaknesses in an athlete's performance that may lead to better running times or a reduced potential for injury. This laboratory focuses on some of the most basic descriptors of running performance—speed, step length, step time, and step rate (step frequency); and consists of two parts, the first focusing on distance running kinematics and the second on sprinting kinematics. *Note: Everyone will be asked to run. Please come to class wearing appropriate clothing and footwear for running.*

Purpose: The purposes of this experiment are (1) to describe the motion of an athlete performing a 25-m run and (2) to demonstrate the relationships that exist between the quantities used to describe the motion (50-m run).

Equipment:		Personnel:	
	Stopwatches		Subjects
	Cones		Starter
	Tape measurement		Recorder
			Timers and step counters

	|	|	|	|	|	|
Start	0	10	20	30	40	50 m Finish

Definitions and Equations:

Stride*—the basic unit of motion for gait reflecting one complete cycle of motion; commonly defined as the motion occurring between successive contacts of the same foot (i.e., right foot contact to next right foot contact)

Step—one half of a complete stride (e.g., right foot contact to left foot contact)

Step length (SL)—the distance traveled per step

Step time (ST)—the time required to complete one step

Step rate (SR)—the rate at which steps are taken (i.e., number of steps per unit of time); inverse of step time (step rate is also known as step frequency)

$$\bar{s} = \ell / \Delta t$$

average running speed = (avg. step length) / (avg. step time)

$$\bar{s} = \overline{SL} / \overline{ST}$$

average running speed = avg. step length $\times$ avg. step rate

$$\bar{s} = \overline{SL} \times \overline{SR}$$

* Note: In much of the popular literature (and in the older scientific literature) the term *stride* has been incorrectly used to mean one half a running cycle (= step). Be careful when you use these terms and when you read the literature. In my opinion (RNH), it is best to avoid the term *stride* altogether, and use the terms *step* and *cycle* so that there is no confusion. McGinnis (2005) prefers to use the term "step". Enoka (1994), however, prefers to use the term "stride" but uses it correctly (stride = 2 steps). Later in this handout (and in your report) you will need to make this distinction.

Procedures:

Part 1 — (STEP LENGTH, STEP RATE, AND SPEED).

The subject runs through the course four times at four different speeds (slow, medium, fast, and "all out"). The subject should try to maintain a constant speed through the 25 m course; therefore he/she will begin 10 m or so in back of the starting line. Two sets of stopwatches will record two different times for the runner: (1) the time to cover 25 m and (2) the time to cover a given number of steps (e.g., 10 steps). Note: The number of complete steps is always one less than the number of foot-strikes. Therefore, begin your count (and your stopwatches) with step zero (0) rather than step one (1). This will give you the correct number of steps.

Average speed is computed by dividing the total distance by the total time. *Average step rate* is computed by dividing the set number of steps by the time it takes to complete those steps. *Average step length* is computed by dividing the *average speed* by the *average step rate* (see equations on previous page).

Part 2 — (VELOCITY AND ACCELERATION PROFILES).

A different subject is used for this part. The subject begins from a stationary position at the starting line. The starter is positioned at the starting line while one or two timers are placed at each of the remaining lines (i.e. 10, 20, 30, 40, and finish lines). The starter signals the timers to synchronously start their watches as the starting signal is given to the subject. As the torso of the subject reaches the 10-m line, the timers standing opposite that line stop their watches. The process is repeated at each of the other lines through the finish line. In effect, we are taking "splits" at 10-m intervals. The times are then recorded on a blackboard. Three trials will be performed and the results averaged between trials. Between trials, the timers should move to a different line to minimize the effect of any one person's timing errors on the results. The purpose of averaging across trials is to reduce error.

Analysis of Data: You should complete the calculations in tables 1, 2, and 3, and answer all questions,

Part 1.

1. Use the data collected in Part 1 to complete Table 1. Note: SL stands for step length and SR stands for step rate. Attach a separate page showing all your calculations.

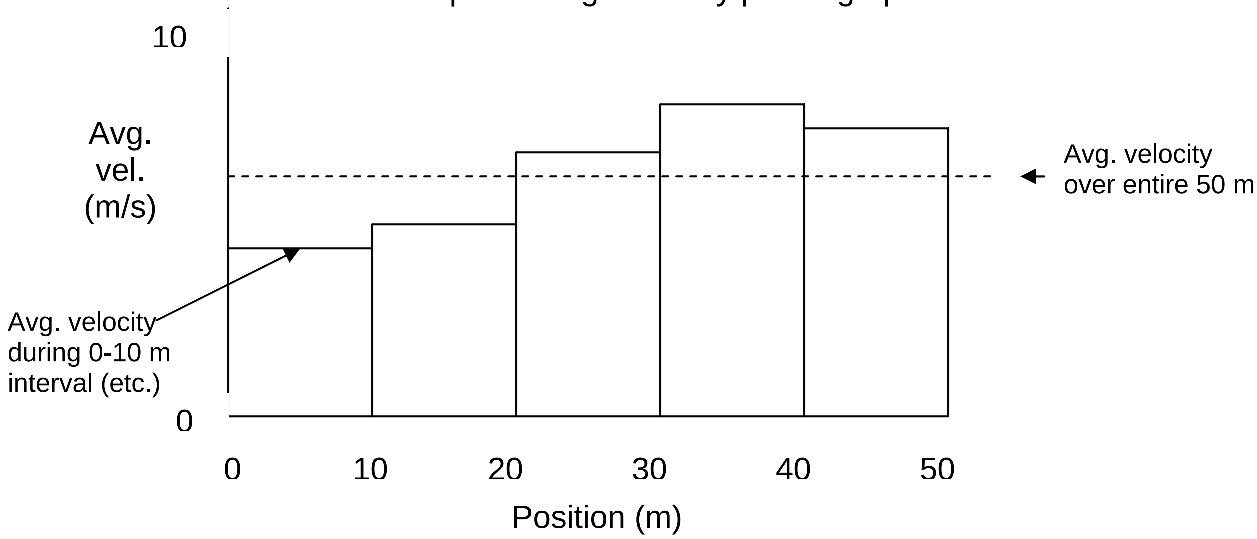
2. Take a piece of graph paper and plot SL and SR as functions of running speed in a similar fashion as shown in Figure 1.12 on page 15 of Enoka (1994, attached). Note, however, that Enoka uses "stride" rather than "step" in this figure. So, in order to make your comparisons, you should divide Enoka's "stride length" in half to get "step length". You should also multiply Enoka's "stride rate" by two to get "step rate". You can do this simply by changing the numbers on the vertical axes of the figure and changing "stride" to "step". Based on your lab data, discuss what happened to SL and SR as running speed increased from slow to medium to fast to "all out". Compare your results to those shown in this Figure 1.12 (after making the aforementioned changes to Enoka's graph). Did our runner behave as expected? If not, speculate as to why not.

Part 2.

1. From the data collected in Part 2, complete Table 2 (attached).

2. Average velocity profile. Calculate the average velocity over each 10 m interval (i.e., 0-10 m, 10-20 m, etc.). Take a piece of graph paper and plot these values in the form of a histogram (bar graph) with velocities plotted as a function of position (see below). In addition, calculate the average velocity over the entire 50 m and indicate this value by a dotted line across the entire histogram. Show all your calculations on a separate page and complete Table 3. Note: Relative values in bar graphs should be able to be interpreted without relying on the numerical scale. Therefore begin the vertical scale for your histograms at zero so that the height of each bar is proportional to its value. This way when one bar is twice as tall as another, it means that the velocity for that interval was twice as large as for the other. It can be misleading to do it any other way.

Example average velocity profile graph



3. Take another piece of graph paper and plot the runner's position (x) as a function of time. From this position vs. time curve, *qualitatively* derive the general shape of the runner's velocity (v) and acceleration (a) curves. Plot these on the attached "blank" graph page showing x, v, and a plotted versus time.

4. After examining all the results, what can you say about the performance of our subject in Part 2? Did he (or she) continue to speed up through the entire run, or slow down a bit at the end? Where was peak velocity reached (in terms of both position and time)?

Lab report due in class, one week from the day of the lab.

Name____________________________________

Table 1. Raw data and results for Part 1.

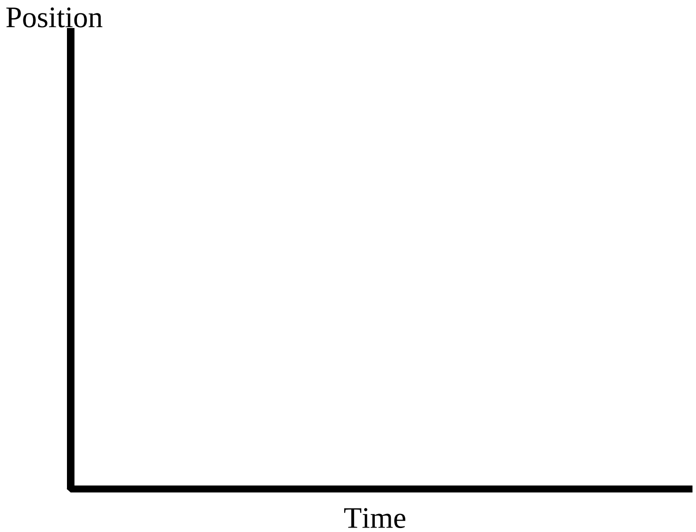
Trial	Distance (m)	Time 1 (s)	Avg. Speed (m/s)	# Steps	Avg. SR (steps/s)	Avg. SL (m/step)
1. slow	25					
2. med.	25					
3. fast	25					
4. all out	25					

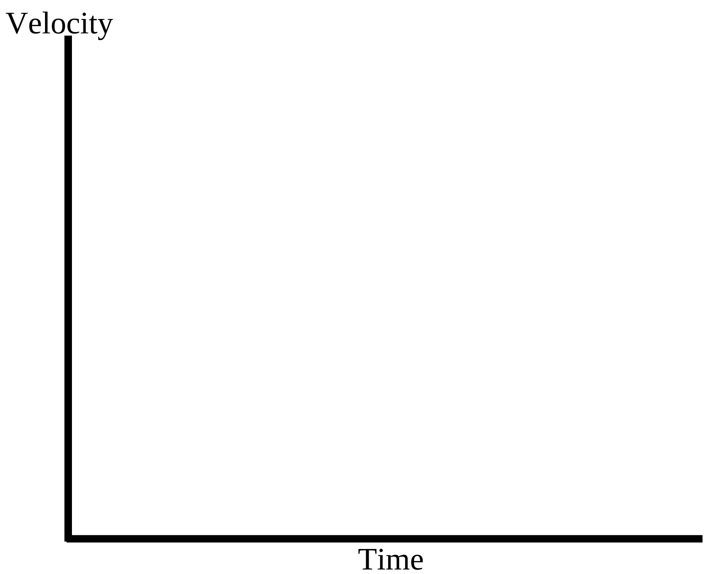
Table 2. Raw data and computed mean split times for Part 2.

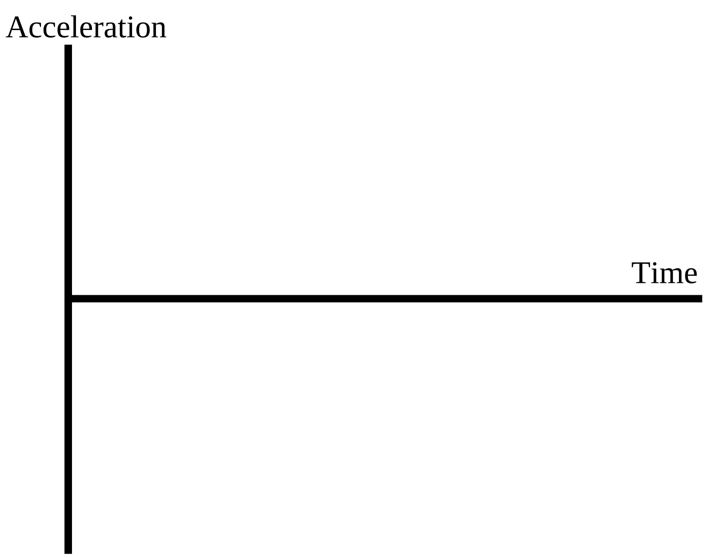
Split Times (s)					
0 m	10 m	20 m	30 m	40 m	50 m
0.00					

Table 3. Computing average velocities at each interval in Part 2.

Variable	Interval					
	0-10 m	10-20 m	20-30 m	30-40 m	40-50 m	0-50 m
d (m)	10	10	10	10	10	50
t (s)						
$\bar{v}$ (m/s)						


Position
Time


Velocity
Time


Acceleration
Time

Human gait has two modes, walking and running. The distinction between the two lies in the percentage of each cycle that the body is supported by foot contact with the ground. During walking (open symbols in Figure 1.10) at least one foot is always on the ground, and for a brief period of each cycle both feet are on the ground; walking can be characterized as an alternating sequence of single and double support. In contrast, running (solid symbols in Figure 1.10) involves alternating sequences of support and nonsupport, with the proportion of the cycle spent in support varying with speed; as speed increases, the time of support decreases (Figure 1.10). But during a single cycle of either walking or running, each limb experiences a sequence of support and nonsupport. The period of support is referred to as the **stance phase**, and the period of nonsupport is known as the **swing phase**. These intervals are separated by two events, the instant at which the foot contacts the ground, or footstrike (FS), and the instant at which the foot leaves the ground, or takeoff (TO). Gait cycles are usually defined relative to these events. For example, one complete cycle, from left foot takeoff to left foot takeoff, is defined as a **stride**.

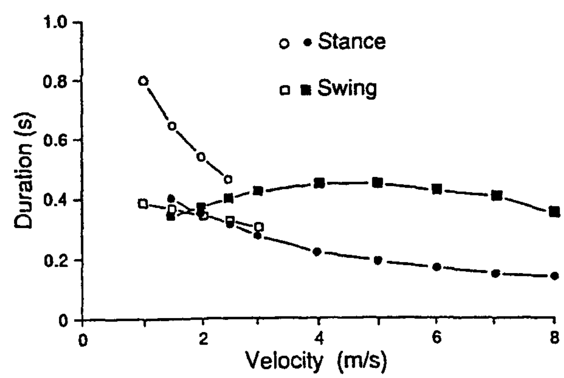


Figure 1.10 Changes in the duration of the stance and swing phases as gait velocity increases.
Note. From "Adaptability in Frequency and Amplitude of Leg Movements During Human Locomotion at Different Speeds" by J. Nilsson and A. Thorstensson, 1987, *Acta Physiologica Scandinavica*, 129, p. 109. Copyright 1987 by Blackwell Scientific Publications. Adapted by permission.

Kinematics of Gait

To illustrate the use of motion descriptors (position, velocity, and acceleration) in the analysis of human movement, let us consider some kinematic characteristics of gait. Human gait involves alternating sequences in which the body is supported first by one limb, which is contacting the ground, and then by the other limb. Although this sounds quite straightforward, its control is complex enough that, despite our technological advances, no machine has yet been built that mimics human gait.

Figure 1.11 summarizes these relationships. The stride contains two steps. A **step** is defined as the part of the cycle from the takeoff (or footstrike) of one foot to the takeoff (or footstrike) of the other foot. Within a stride, four events of footstrike and takeoff occur, two for each limb. These are right footstrike (rFS), right takeoff (rTO), left footstrike (lFS), and left takeoff (lTO). The swing phase exists between the events of TO and FS, whereas stance occurs from FS to TO. Figure 1.11 shows how the durations of the stride and of the stance and swing phases change with gait speed.

From: Enoka, R.M. (1994). Neuromechanical Basis of Kinesiology, 2nd Edition. Champaign, IL: Human Kinetics, pp. 14-19.

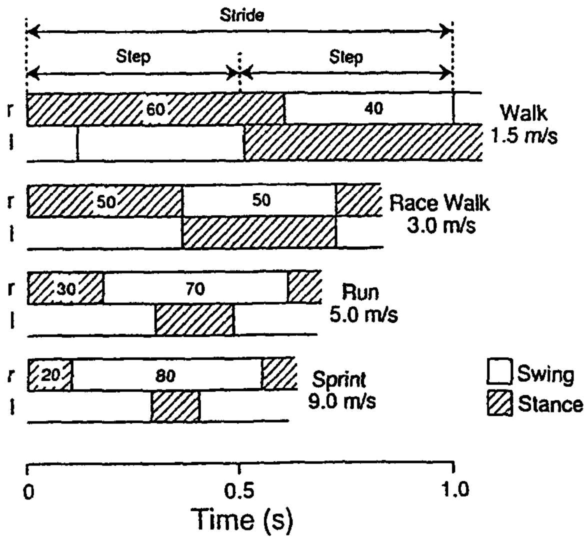


Figure 1.11 The events and phases characterizing walking and running gaits (r = right; l = left).
Note. From "Biomechanics of Running Gait" by C.L. Vaughan, 1984, *CRC Critical Reviews in Biomedical Engineering*, 12, p. 6. Copyright 1984 by CRC Press, Inc. Adapted by permission.

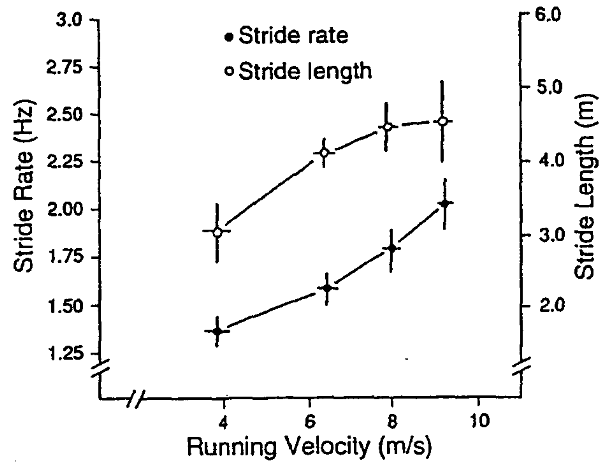


Figure 1.12 Average changes in stride length and stride rate with running velocity.
Note. From "Mechanical Factors Influencing Running Speed" by P. Luhtanen and P.V. Komi. In *Biomechanics VI-B* (p. 25) by E. Asmussen and K. Jorgensen (Eds.), 1978, Baltimore: University Park Press. Copyright 1978 by University Park Press.

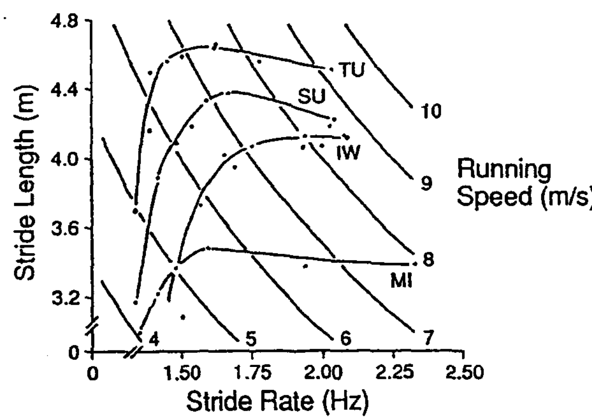


Figure 1.13 The relationships among stride rate, stride length, and running speed.
Note. From "Temporal Patterns in Running" by M. Saito, K. Kobayashi, M. Miyashita, and T. Hoshikawa. In *Biomechanics IV* (p. 107) by R.C. Nelson and C.A. Morehouse (Eds.), 1974, Baltimore: University Park Press. Copyright 1974 by University Park Press.

Stride Length and Rate

Running speed depends on two variables, stride length and stride rate (Vaughan, 1984). If stride length remains constant, then as stride time decreases (i.e., stride rate increases) running speed increases. If stride rate remains constant, speed increases as stride length increases. These effects of stride rate and stride length on running speed are illustrated in Figure 1.12. Within certain limits a number of length-rate combinations will produce a desired speed. The average combinations are shown in Figure 1.12. For example, an individual running at a speed of 8 m/s will use a stride rate of about 1.75 Hz and a stride length of about 4.6 m. Figure 1.12 illustrates that, on average, a runner increases speed over the range from 4 to 9 m/s by increasing stride rate continually, although more slowly (the slope is not that steep) at lower velocities, but only increases stride length up to about 8 m/s. Notice that the contribution of changes in stride length and rate to running velocity are different at low and high velocities; this is apparent by the differences in the slope of each curve (stride length and rate) at different velocities.

In contrast to the average data shown in Figure 1.12, the strategy adopted by four runners for increasing running speed is depicted in Figure 1.13. The data were obtained by measuring stride length from footprints and stride rate from foot switches that indicated the stance phase. Consider the results obtained for Subject SU, whose change in speed from 4.3 to 8.5 m/s seemed to be accomplished in two phases: Initial changes in speed (4.3 to 7.0 m/s) were due to a combined increase in stride length (3.2 to 4.4 m) and stride rate (1.4 to 1.7 Hz); subsequent speed increases (7.0 to 8.5 m/s) were achieved by a slight decrease in stride length (about 20 cm) and a sustained increase in stride rate (1.7 to 2.0 Hz). In general, the trained runners (Subjects TU, SU, and IW) increased stride length up to 7.0 m/s, whereas the untrained runner (MI) did so only up to about 5.5 m/s. All four runners, however, achieved initial increases in speed (up to 6.0 m/s for the trained runners) mainly by increasing stride length. Clearly, the combination of stride length and rate chosen to achieve a desired speed varies among runners. Furthermore, it seems that anthropometric variables (e.g., stature, leg length, limb segment mass) are not the primary determinants of preferred stride frequency and length (Cavanagh & Kram, 1989). The typical explanation given for the strategy of changing stride length rather than rate is that it requires less energy to lengthen the stride within reasonable limits than to increase stride rate.

Kinematic Effects of Speed

Increasing running speed by increasing stride length requires an alteration of the kinematics of the limbs. The changes needed include both the range of motion about a joint (quantity) and the pattern of displacement (quality). For example, Figure 1.14 shows that angular displacement about the knee joint increases as the runner goes from a walk to a run and that the stance phase (indicated by the shaded horizontal bar) includes only knee extension during a sprint but both flexion and extension during walking and running. Similarly, as running speed increases, there is an increase in arm motion, which includes an increase in the range of motion about both the shoulder and elbow joints. As a consequence of these changes, the vertical displacement of the whole-body center of gravity is reduced as speed increases (Cavagna, Saibene, & Margaria, 1964).

Performance variables that do not differ between runners capable of running 9 m/s and those who can achieve 11 m/s include (a) step length, (b) the minimum distance between the heel and the buttocks during the swing phase, (c) vertical velocity at takeoff, and (d) the height of the foot during the swing phase as it passes the support leg. In contrast, those runners who can achieve 11 m/s exhibit (a) a 15% greater stride rate, (b) less time in the stance phase, (c) a shorter horizontal distance between the foot and a vertical projection of the center of gravity at takeoff, (d) a less extended knee joint at takeoff, and (e) a more vertical trunk position. These differences demonstrate that the maximum running speed that an individual can achieve is influenced by the kinematic details of the movement.

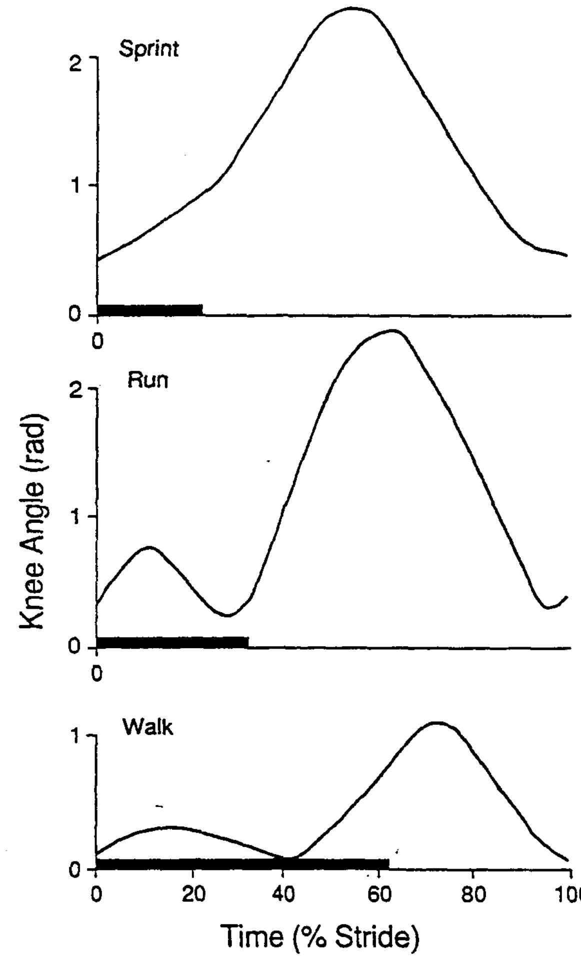


Figure 1.14 Knee angle during a stride for a walk, run, and sprint. A knee angle of 0 rad indicates complete extension.

Note. From "Biomechanics of Running Gait" by C.L. Vaughan, 1984, *CRC Critical Reviews in Biomechanical Engineering*, **12**, p. 11. Copyright 1984 by CRC Press, Boca Raton, Florida. Adapted by permission.

Angle-Angle Diagrams

Cyclical activities, such as walking and running, are ideal movements to represent in angle-angle diagrams because the beginning and the end of an event are located at about the same point on the diagram. This type of diagram has proved useful in comparing movement forms (Hershler & Milner, 1980a, 1980b; D.I. Miller, 1978). For example, comparing the knee-thigh diagram of a normal subject during running with that of a subject who has had a lower extremity amputated can be useful in evaluating the effectiveness of prostheses in restoring normal-looking gait. In this type of analysis, emphasis is placed on comparing the shape of the respective angle-angle diagrams (e.g., Figures 1.15 vs. 1.16).

The interpretation of Figure 1.15 involves following the curve around in a counterclockwise direction. This diagram illustrates the angle-angle diagram for one limb during a running stride. As mentioned previously, each limb experiences two events during a stride, footstrike (FS) and takeoff (TO). From footstrike to takeoff (stance phase—dotted line), the foot is in contact with the ground. Conversely, from takeoff to footstrike (swing phase—solid line), the foot of the illustrated limb is not in contact with the ground. In addition, during the swing phase (lTO to lFS), the other foot first contacts and then leaves the ground (rFS to rTO). Accordingly, Figure

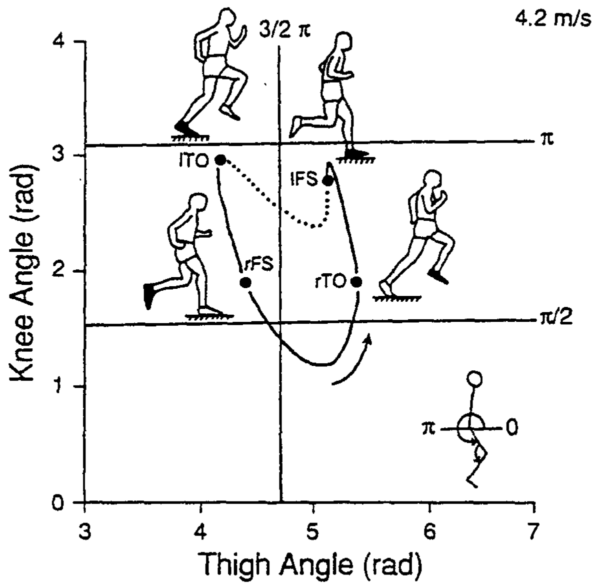


Figure 1.15 Knee-thigh diagram of the left limb of a skilled runner.
Note. From "Below-Knee Amputee Running Gait" by R.M. Enoka, D.I. Miller, and E.M. Burgess, 1982, *American Journal of Physical Medicine*, **61**, p. 70. Copyright 1982 by Williams and Wilkins. Reprinted by permission.

1.15 reveals that (a) after lTO, the thigh rotates forward about the hip joint and the knee flexes to a minimum angle; (b) following the minimum angle, the knee extends until just before lFS while the thigh continues to rotate forward and then begins rotating backward; and (c) during stance (lFS to lTO), the knee first flexes and then extends, while the thigh rotates backward.

Angle-angle diagrams have several important features, and these features are apparent in Figure 1.15. A relative angle (knee) is plotted against an absolute angle (thigh). The graph illustrates the combined actions of the knee flexion-extension and thigh forward-backward rotation. In addition, three reference axes are shown with which to evaluate the range of motion of the movement: (a) The 3/2 π axis indicates a thigh angle at which the thigh would be in a vertical position, (b) the π axis (3.14 rad) represents a knee angle of complete extension, and (c) the π/2 axis shows a right angle (1.57 rad) for the knee joint. According to Figure 1.15, therefore, the thigh passes in front of and behind the 3/2π line, the knee joint is never fully extended, and the smallest knee angle is less than a right angle during a normal running stride at 4.2 m/s.

In contrast to this normal knee-thigh diagram, the three graphs for subjects with below-knee amputations depicted in Figure 1.16 indicate a substantial difference during the stance phase (i.e., the region from lFS to lTO). Specifically, the amputee knee-thigh diagrams reveal a knee-joint pattern of a constant angle followed by flexion rather than the normal flexion-extension sequence. Because Figure 1.16 shows the knee-thigh diagrams for the prosthetic limbs of the below-knee amputees, the pattern of the graphs is perhaps not surprising. The failure to flex the knee during stance, shown in Figure 1.16 by the knee angle not decreasing immediately after FS, means that the amputees just used their limbs as a rigid lever about which to rotate while the prosthetic foot was on the ground. This type of graphic display could be used in a clinical setting to monitor a rehabilitation program aimed at correcting this strategy so that the gait would appear more normal.

Angle-angle diagrams have also been used to represent the kinematics of the arms during running. Because the motion of the arms is frequently not confined to the sagittal plane during running, imaging techniques that can capture three-dimensional motion are necessary. When this is done, the displacement of the upper arm about the shoulder and the relative angle between the upper and lower arms (elbow angle) for an individual running at 11.4 m/s has the form shown in Figure 1.17.

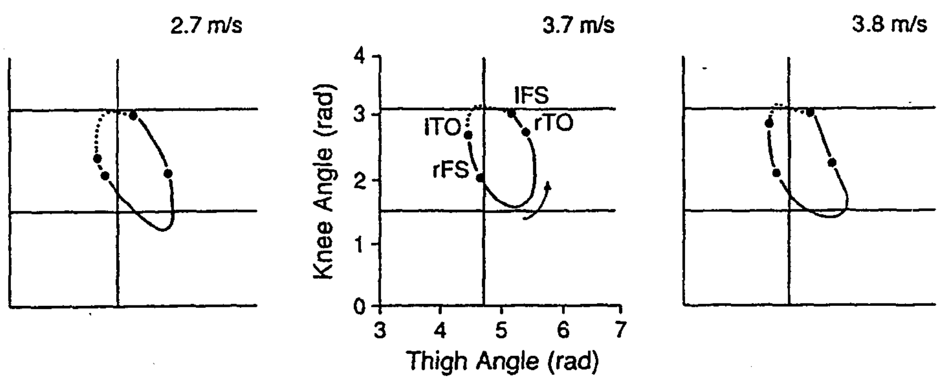


Figure 1.16 Knee-thigh diagrams for three below-knee amputees running at speeds from 2.7 to 3.8 m/s.
Note. From "Below-Knee Amputee Running Gait" by R.M. Enoka, D.I. Miller, and E.M. Burgess, 1982, *American Journal of Physical Medicine*, **61**, p. 78. Copyright 1982 by Williams and Wilkins. Reprinted by permission.

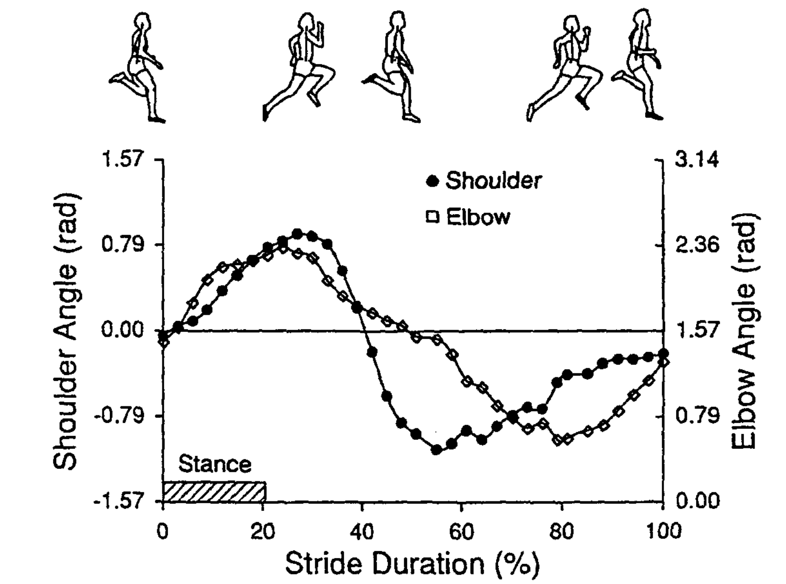


Figure 1.17 Displacement about the right shoulder and elbow joints during a running stride.
Note. From "Temporal and Kinematic Analysis of Arm Motion in Sprinters" by C. Li and A.E. Atwater, 1984, Presented at the Olympic Scientific Congress, Eugene, OR. Reprinted by permission.

A positive shoulder angle indicates flexion (forward of vertical) and a negative one represents extension (backward of vertical). Of course, the amplitude and timing of the displacement vary as a function of running speed (Lusby & Atwater, 1983). Although Figure 1.17 includes information on the timing of the displacement at the two angles, this information can be presented more succinctly in an angle-angle diagram (Figure 1.18). Essentially, the pattern of displacement about the shoulder and elbow joints is confined to the upper right and lower left quadrants of the angle-angle diagram. The upper right quadrant represents concurrent shoulder and elbow flexion, whereas the lower quadrant indicates concurrent shoulder and elbow extension. The stance phase of the ipsilateral leg (rFS to rTO in Figure 1.18) is mainly accompanied by concurrent flexion at the two joints. But the pattern is not one of a tight coupling of the two actions (i.e., flexion or extension), because there are instances when opposing motion occurs at the two joints. Can you see where this occurs in Figure 1.18? One example is in the phase from lFS to lTO when the shoulder extends and the elbow flexes. The elbow-shoulder angle-angle diagrams, like those for the leg, provide a qualitative means to evaluate the pattern (i.e., shape or structure) of the movement.

Another useful feature of these cyclic angle-angle diagrams is that, in addition to shape comparisons, the size of the diagram indicates the range of motion experienced at each joint during the event. For example, we would expect that increases in stride length as a runner increases speed are due to changes in the range of motion (amount of motion) at various lower extremity joints.

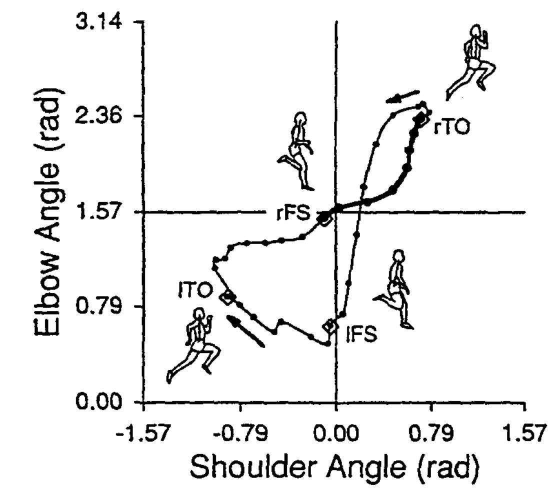


Figure 1.18 Elbow-shoulder angle-angle diagram based on the data shown in Figure 1.17.
Note. From "Temporal and Kinematic Analysis of Arm Motion in Sprinters" by C. Li and A.E. Atwater, 1984, Presented at the Olympic Scientific Congress, Eugene, OR. Reprinted by permission.

Figure 1.19 confirms this expectation by showing that, as speed increases (3.9 vs. 7.6 m/s), the amount of rotation both of the thigh and about the knee joint increases; the larger angle-angle diagram represents the faster speed.

At this point a good exercise to test your grasp of the angle-angle diagram approach is to sketch a knee-thigh diagram as a runner goes uphill and then downhill (Milliron & Cavanagh, 1990). The key to this exercise

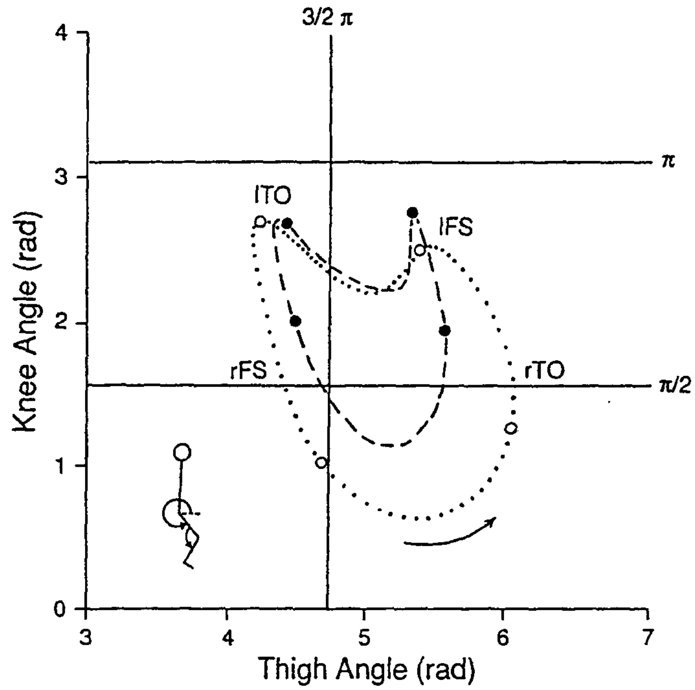


Figure 1.19 Knee-thigh angle-angle diagram as a function of running speed.
Note. Adapted from Miller, Enoka, McCullough, Burgess, Hutton, and Frankel, 1979.

is to think of how the movement would change relative to the three reference axes. For example, it seems reasonable to expect that, compared with a runner on level ground, a runner going uphill would extend the knee less, flex the knee less at the minimum angle, and have the thigh remain in front of vertical (forward rotation) for a greater part of the stride. Try sketching this relationship.

The angle-angle diagram format, first proposed by Cavanagh and Grieve (1973), has largely been confined to representing position information. Some investigators (e.g., D.I. Miller, 1978) have experimented with plots of angular velocity and acceleration, but these attempts have not been readily accepted, probably due to the complexity of the relationships. Similarly, given current computer graphics capabilities, it is surprising that no three-dimensional angle-angle diagrams, with time (e.g., running speed) as the third axis, have yet been published.