Human Walking

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THIRD EDITION

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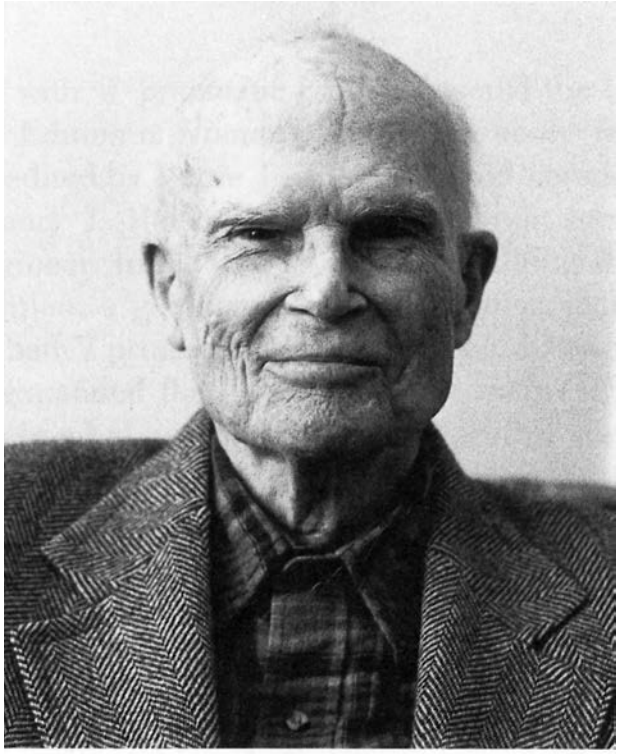
To Will, Thomas, Jamie, Justin, Laura, Jeffrey, Jayson, Jared and all the other children of the world.

IN MEMORIAM

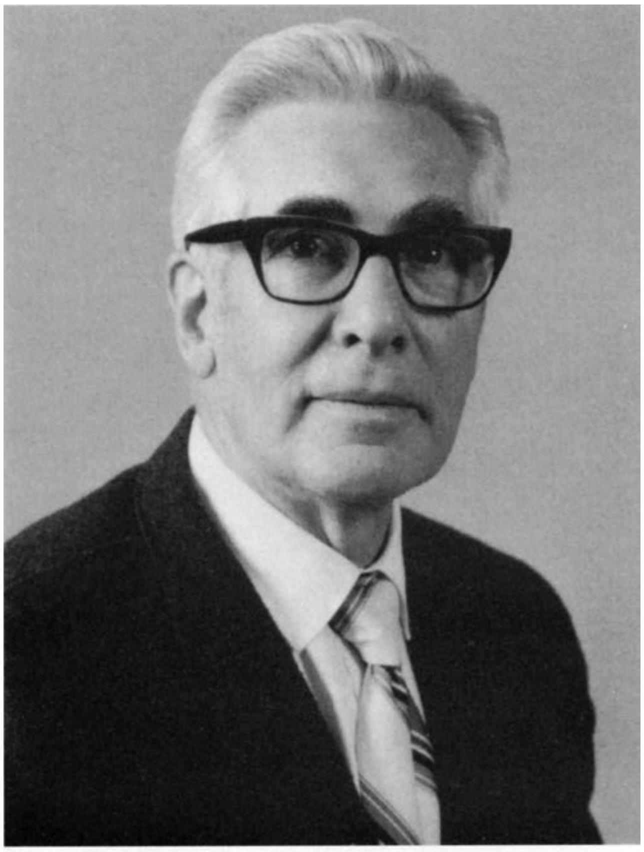


Henry J. Ralston, PhD
1906–1993

Henry J. Ralston, Professor of Physiology, University of California School of Medicine, San Francisco, co-authored the 1st edition of *Human Walking*. Dr. Ralston was an internationally renowned investigator in the physiology and biophysics of human locomotion.Dr. Ralston was also a talented teacher, educating several generations of neuromuscular physiology students as part of the Physical Therapy and Medicine Departments at the University of California at San Francisco as well as teaching general physiology for nearly three decades.

Known to his friends, family, and colleagues as "Bip," a name given to him as an infant, Ralston was a descendant of a family that came to San Francisco from Scotland in the early 1860s; the family started an iron works company that survived until the Depression. Ralston worked his way through the University of California at Berkeley as a newspaper writer and initiated the first regular column in San Francisco reviewing and critiquing radio programs. His PhD thesis concerned the biological effects of ionizing radiation.

Just after World War II, Dr. Ralston began the collaboration with Dr. Verne T. Inman that would result in a series of major contributions to the field of human locomotion. Supported by funding from various federal agencies, Inman and Ralston began the Lower Extremity Amputee Research Laboratory, which soon evolved into the Biomechanics Laboratory. With colleagues in bioengineering at the University of California at Berkeley, as well as with physicians and scientists at the University of California at San Francisco, the laboratory pioneered work that revolutionized the design of lower limb prosthetic devices. His physiological investigations focused on neuromuscular physiology and the energetics of walking and led to improved surgical approaches to lower limb repair and enhanced design of prostheses. *Human Walking* was a culmination of Dr. Ralston's ground breaking research and his collaboration with Dr. Inman.



Verne T. Inman, MD, PhD
1905–1980

Verne T. Inman, Professor Emeritus and former Chairman of the Department of Orthopaedic Surgery, University of California School of Medicine, San Francisco, co-edited the 1st edition of *Human Walking*.

Dr. Inman was born in San Jose, California, November 6, 1905. He received both his medical education and formal training in human anatomy at the University of California.

Dr. Inman's primary research interest since his student days may be best described as functional anatomy. His studies on the actions of the shoulder joint, the clavicle, the abductor muscles of the hip, and the ankle are classics in the field. He was one of the pioneers in the use of electromyography to analyze muscle function.

Shortly after World War II, Dr. Inman, along with colleagues in engineering and physiology, became involved in lower limb prosthetics research. This led to the formation of the Biomechanics Laboratory at the University of California at San Francisco and Berkeley, of which he was director from 1957 to 1973 and consultant until his death.

Dr. Inman had long expressed the wish to prepare a book summarizing the research studies on human walking in the Biomechanics Laboratory, and *Human Walking* is the culmination of that wish.

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PREFACE

The third edition of *Human Walking* embraces the multidisciplinary approach and pragmatic spirit that was a major theme of the first and second editions. The increased breadth and depth of material for the third edition reflects the expanding nature of the field. Our understanding of human walking and the information available has increased exponentially over the past decade. New areas of knowledge have developed over the last several years in fields such as physical anthropology, neuromotor development, and biomechanics, with groundbreaking advances in biomechanical modeling and artificial walking. Increasingly precise measurement techniques have made it possible to study the neuromuscular activation and intricate biomechanics of human walking and have deepened our understanding of the neurological and musculoskeletal mechanisms underlying walking disorders. The third edition summarizes and integrates this new information with our classical understanding of human walking.

The first edition of *Human Walking,* published in 1981, was written by an interdisciplinary team of investigators, composed of Verne T. Inman, an orthopedic surgeon, Henry J. Ralston, a physiologist, and Frank Todd, an engineer. In the years following the publication of the first edition, a generation of students and researchers used *Human Walking* as both a primary text and a reference as they expanded the available knowledge in the field of motion analysis. In the second edition, we chose to preserve the multidisciplinary approach as well as the pragmatism of the previous edition, while extending the scope and the scale of the book. We invited a diverse group of distinguished contributors to share their ideas, information, and expertise. The third edition expands on this theme. We have preserved the classic and original chapter "Human Locomotion" written by Verne T. Inman, Henry J. Ralston, and Frank Todd, and added commentary on the determinants of gait that integrates new information. There are updated chapters on Kinematics of Normal Walking, Kinetics of Normal Walking, Energetics of Walking, Muscle Activity During Walking, Development of Gait, Clinical Gait Analysis, Lower Limb Prostheses and Restoring Walking After Paralysis. Furthermore, we have expanded the multidisciplinary approach to include new chapters on rapidly developing fields such as The Evolution of Human Walking, Gait Adaptations in Adulthood, Walking for Health, and Simulation of Walking. It was clear a decade ago that biomechanical modeling would make interesting contributions to our understanding of human walking. However, it was not certain how rapidly these contributions would come and how important they would ultimately be for identifying the sources of pathological gait. Chapter 12, "Simulation of Walking," shows just how valuable biomechanical modeling can be and provides a fresh understanding of the scientific basis for the treatment of patients with walking disorders. Biomechanical modeling is now used in the clinical setting to plan such surgical procedures as tendon transfers, tendon lengthenings, and osteotomies. The final chapter, "Six Take-Home Lessons," summarizes some of the essential elements of human walking for students who are new to the field.

Human walking is an extremely complex activity whose apparent simplicity disappears when one attempts a quantitative or even qualitative description of the process. Fortunately, the theories and techniques of modern motion analysis have markedly improved our ability to describe and understand normal and pathological ambulation. Much of the current success is a result of the wide interest in human walking as demonstrated by a diverse group of clinicians and scientists currently working in the field, including orthopaedic surgeons, physical therapists, bioengineers, physiatrists, neurologists, orthotists, prosthetists and exercise physiologists. The third edition of *Human Walking* is geared to this diverse group of students, researchers, and clinicians, and continues the pragmatic tradition of providing useful information from a broad spectrum of expertise while offering a springboard for future advances in the field by the next generation.

Jessica Rose
James G. Gamble
September 2005

Human Locomotion

Verne T. Inman, Henry J. Ralston, and Frank Todd
Commentary by Dudley S. Childress and Steven A. Gard

Locomotion, a characteristic of animals, is the process by which the animal moves itself from one geographic position to another. Locomotion includes starting, stopping, changes in speed, alterations in direction, and modifications for changes in slope. These events, however, are transitory activities that are superimposed on a basic pattern. In walking and running animals, this pattern can be defined as a rhythmic displacement of body parts that maintains the animal in constant forward progression.

The majority of mammals are quadripedal. When walking slowly, quadripeds tend to coordinate their four limbs so that three of their feet are on the ground. A crawling infant uses its limbs in a sequence that is essentially quadripedal, only advancing one while the other three support its body on the floor. This provides the stability of a tripod. This stability is lost when the animal becomes bipedal, and while bipedal locomotion seems simpler, it requires greater neural control. The mastering of the erect bipedal type of locomotion is a relatively prolonged affair and appears to be a combination of instinct and learning.

If walking is a learned activity, it is not surprising that each of us displays certain personal peculiarities superimposed on the basic pattern of bipedal locomotion. Physical anthropologists have studied the differences between races and measured the variations in skeletal parts. Anatomists are aware of the presence of individual variations. All of us are aware that individuals walk differently; one can often recognize an acquaintance by his manner of walking even when seen at a distance. Tall, slender people walk differently from short, stocky people. People alter their manner of walking when wearing shoes with different heel heights. A person walks differently when exhilarated than when mentally depressed. With these ideas in mind, one may legitimately question the usefulness of anthropometric data and averages in furthering our understanding of human walking.

Certainly everyone has his own idiosyncratic way of walking, and there is no such thing as an average person. However, most of us do walk with reasonable facility and, as will be shown later, with surprising efficiency. A conclusion that seems inescapable is that each of us learns to integrate the numerous variables that nature has bestowed on our individual neuromusculoskeletal systems into a smoothly functioning whole. Obviously, our bipedal plantigrade type of progression imposes gross similarities on our manner of walking. These are easily identified. We must oscillate our legs, and as we do our bodies rise and fall with each step. The movements parallel to the plane of progression are large, and the individual variations in relation to the size of the total angular displacements are relatively small. When these aspects of human walking are considered, the use of average values helps to develop a general understanding of the basic relationships that exist between the major segments of the lower limb. Upon these basic activities are superimposed numerous less obvious movements of individual parts of the body. These small movements occur in planes closer to the coronal and transverse planes of the body, and in these small movements, the individual variations are much greater.

Furthermore, when the locations of axes of movement are determined and ranges of motion measured both in the cadaver and in the living, marked individual differences are disclosed. The differences in these small movements bestow on each of us a distinctive manner of walking. Here, the use of average values can hinder the recognition of certain interrelationships that must exist between the participating joints. This is particularly true when one is trying to understand the functional behavior of the joints of the ankle and foot.

A hypothesis is easily formulated that seems to explain most observations, including the peculiar behavior of the major segments of the body during walking. This hypothesis states that the human body will integrate the motions of the various segments and control the activity of the muscles so that the metabolic energy required for a given distance walked is minimized. In later sections, it will be shown that any interference with normal relationships between various segments of the body invariably increases the metabolic cost of walking.

PROCESS OF WALKING

The term *walking* is nonspecific. Its connotation is that of a cyclic pattern of body movements that are repeated over and over, step after step. Consequently, descriptions of walking customarily deal with what happens in the course of just one cycle, with the assumption that successive cycles are all about the same. Although this assumption is not strictly true, it is a reasonable approximation. Apart from the multiple variations that may occur between different individuals or within the same individual as a result of changes in the speed of walking, or such factors as alterations in footwear, there are certain observable events that are shared by all.

Human walking is a process of locomotion in which the erect, moving body is supported by first one leg and then the other. As the moving body passes over the supporting leg, the other leg swings forward in preparation for its next support phase. One foot or the other is always on the ground, and during that period when the support of the body is transferred from the trailing to the leading leg there is a brief period when both feet are on the ground. As a person walks faster, these periods of double support become smaller fractions of the walking cycle until, eventually, as a person starts to run, they disappear altogether and are replaced by brief periods when neither foot is on the ground. The cyclic alternations of the support function of each leg and the existence of a transfer period when both feet are on the ground are essential features of the locomotion process known as walking.

In the act of walking there are two basic requisites: (1) continuing ground reaction forces that support the body, and (2) periodic movement of each foot from one position of support to the next in the direction of progression. These elements are necessary for any form of bipedal walking no matter how distorted by physical disability. They are equally necessary when prosthetic or orthotic devices are used.

These two basic requisites of walking give rise to specific body motions that are universally observable during walking. As the body passes over the weight-bearing limb, three different deviations occur from uniform progression in a straight line. With each step, the body speeds up and slows down slightly, it rises and falls a few centimeters, and it weaves slightly from side to side. These motions are related to one another in a systematic fashion.

The body must slow down and then speed up again during each step because the support provided by the legs does not remain directly under the body at all times. A supporting foot starts out ahead of the body where it tends to slow the body down, and then it passes under the body and to the rear, where it tends to speed the body up again. This motion is difficult to see, but easy to sense when a person carries a shallow pan of water. It is almost impossible to prevent the water from surging backward and forward as a result of the alternating accelerations and decelerations of the body.

As the body passes over the supporting leg, it rises until the foot is directly underneath and then descends again as the foot passes behind. The highest point in elevation occurs when the speed is lowest, and the lowest point in elevation occurs when the speed is highest.

During the period of single support, the body also tends to shift laterally over the support limb. The pelvis achieves its maximal lateral displacement somewhat after midstance and then starts back toward the other side. The amount of lateral sway increases when the tread width is increased. While individual variations in the measured magnitudes of these motions will always be observed in any group of people, the motions will be present to some degree in everyone. Normally there is symmetry in the movement, and the patterns repeat themselves with each successive cycle.

Although the displacements of the entire body through space may be described as translational, this translation is achieved by the angular displacements of various segments of the body about axes that lie in the proximity of joints. A principal task in describing human locomotion is to measure the angular displacements of the various segments during the translational movement of the body as a whole. Because the translational movements are the final product of the angular displacements of the individual segments, and these are easily discernible and measurable, they may be used as one set of parameters for the description of the walking cycle. However, a description that deals solely with movement and ignores the forces that produce these motions constitutes only a small part of the entire story of human walking.

MAJOR DISPLACEMENTS OF THE BODY DURING WALKING

Synchronous movements of nearly all the major parts of the body occur during walking at moderate speeds. The pelvis lists, rotates, and undulates as it moves forward. The segments of the lower limb show displacements in all three planes of space, while the shoulders rotate and the arms swing out of phase with the displacements of the pelvis and legs. It seems reasonable to begin the description of walking with a discussion of the translation of the body as a whole through space. To do this, the concept of the pathway of the center of mass of the body will be used. The center of mass of any body is a point such that if any plane is passed through it, the mass moments on one side of the plane are equal to the mass moments on the other. If the body is suspended at this center of mass, it will not tend to tip in any direction. During walking, the center of mass of the body, although not remaining in an absolutely fixed position, tends to remain within the pelvis. This is

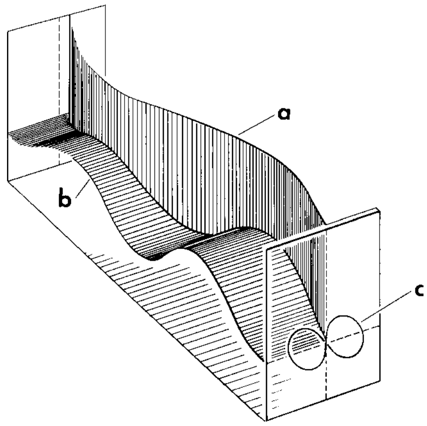

FIGURE 1-1. Displacements of center of mass in three planes of space during single stride (cycle). The actual displacements have been greatly exaggerated. (**A**), Lateral displacement in a horizontal plane; (**B**), vertical displacement. Combined displacements of **A** and **B** as projected onto a plane perpendicular to the plane of progression are shown in **C**.

convenient for two reasons. Measurements of the movements of the pelvis in the three planes of space are readily made, and the pelvis becomes a suitable structure to separate the body into upper and lower parts, which behave differently during walking.

In normal level walking, the center of mass describes a smooth sinusoidal curve when projected on the plane of progression (Fig. 1-1). The total amount of vertical displacement in normal adult men is typically about 5 cm at the usual speeds of walking. The summits of these oscillations appear at about the middle of the stance (foot on ground) phase of the supporting limb. The opposite limb is at this time in the middle of its swing (foot off ground) phase. The center of mass falls to its lowest level during the middle of double weightbearing, when both feet are in contact with the ground. The curve is remarkably smooth and is found to fluctuate evenly between maxima and minima of displacements, with few irregularities. It is interesting to note that at their maximal vertical displacement, the head and the center of mass are slightly lower than when the subject is standing on both feet. In other words, in a smooth walk, a person is slightly shorter than when he is standing, so that if he were to walk through a tunnel the height of which corresponded exactly to his standing height he could do so without fear of bumping his head.

The center of mass of the body is also displaced laterally in the horizontal plane. In this plane, too, it describes a sinusoidal curve, the maximal values of which alternately pass to the right and to the left in association with the support of the weight-bearing limb. The curve is sinusoidal, at one-half the frequency of the vertical displacement.

When viewed from the back, the body is seen to undulate up and down and swing from side to side during each cycle. If the vertical and lateral displacements are considered as pure sine waves, with the frequency of the vertical displacements being precisely twice that of the lateral displacements and the peaks being achieved at the same time, then the curve of displacement of the center of mass, as projected onto a plane at right angles to the line of progression, is in the form of a "U." At higher speeds of walking, this situation is approximated; at lower speeds, however, the peak of the curve for vertical displacement is reached slightly before the peak of lateral displacement. This causes the curve of movement of the center of mass as projected on a coronal plane (a vertical plane at a right angle to the line of progression) to resemble a slightly distorted lazy 8 (Fig. 1-2).

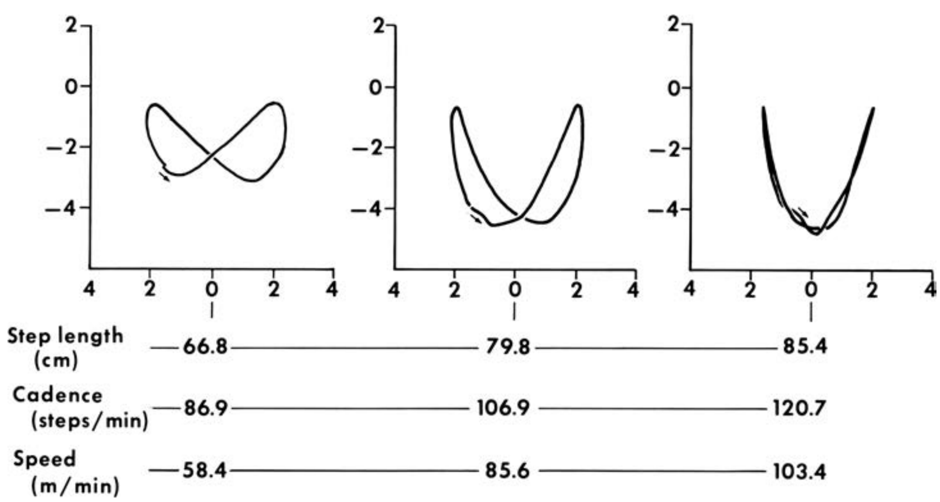

FIGURE 1-2. Effect of variations in speed on displacement of pelvis as projected onto plane perpendicular to plane of progression (see Fig. 1-1**C**).

For the sake of simplicity, a series of models will be employed to illustrate how the smooth sinusoidal displacement pathway is achieved in bipedal locomotion (5,6). The first model will show the body as consisting solely of a bar representing the pelvis, with the center of mass depicted as a small block lying midway between the two hips (Fig. 1-3). The legs will be represented as rigid levers without foot, ankle, or knee mechanisms, articulated only at the hip joints, which will permit flexion and extension only. Such a system of quasilocomotion would produce something analogous to the process of stepping off distances with a pair of compasses or dividers, the pathway of the center of mass of such a system being a series of intersecting arcs.

The radius of each arc would be equal to the length of the limbs, and with each step, the extent of flexion and extension of the hip joint would be the same. Locomotion of this type might be imitated, but imperfectly, by walking on one's heels with the knees fixed in extension. Such a type of locomotion would require that the center of mass be elevated to a height equal to the height of the center of mass in the standing person; it would also result in a severe jolt at the point of intersection of each two arcs, where there is an abrupt change in the direction of movement of the center of mass. Decreasing the total elevation, depressing the center of mass, and smoothing the series of interrupted arcs require coordinated movements involving all the joints of the lower limb. These individual movements can be considered as elements that contribute to the total process of walking. A qualitative description of the principal elements is presented in the following paragraphs to provide a basis for the quantitative descriptions in later chapters.

Pelvic Rotation

In normal level walking, the pelvis rotates about a vertical axis alternately to the right and to the left, relative to the line of progression. At the customary cadence and stride of typical people, the magnitude of this rotation is approximately 4 degrees on either side of the central axis, or a total of some 8 degrees. This value usually increases markedly when speed is increased. Because the pelvis is a rigid structure, the rotations occur alternately at each hip joint and require a deviation from pure flexion and extension of the hips.

The significance of pelvic rotation can best be appreciated by a study of the theoretical model (Fig. 1-4). The effects of pelvic rotation are to flatten somewhat the arc of the passage of the center of mass in compass gait by elevating the ends of that arc. In consequence, the angles at the intersections of successive arcs are rendered less abrupt and, at the same time, are elevated in relation to the summits. In this way, the severity of the impact at floor contact is reduced. The force required to change the direction of the center of mass in the succeeding arc of translation is less, and the angular displacement at the hip in flexion and extension is reduced.

Pelvic List

In normal walking, the pelvis lists downward in the coronal plane on the side opposite to that of the weight-bearing limb (positive Trendelenburg). At moderate speeds, the alternate angular displacement is about 5 degrees. The displacement occurs at the hip joint, producing an equivalent relative adduction of the supporting limb and relative abduction of the other limb, which is in the swing phase of the cycle. To permit pelvic list, the knee joint of the non–weight-bearing limb must flex to allow clearance for the swing-through of that member.

The effects of pelvic list on the pathway of the center of mass are evident in the experimental model (Fig. 1-5). As the lateral list occurs while the body is passing over the vertical supporting member in early stance phase, the center of mass is lowered. Thus, the summit of the arc is lowered, further flattening the pathway. In addition and perhaps more importantly, pelvic list contributes to the effectiveness of the abductor mechanism of the hip (the abductor muscles and iliotibial tract). The latter effect will be discussed in greater detail in the section on the phasic action of muscles (see Chapter 6).

Knee Flexion in Stance Phase

A characteristic of walking at moderate and fast speeds is knee flexion of the supporting limb as the body passes over it. This supporting member enters stance phase at heel strike with the knee joint in nearly full extension. Thereafter, the knee joint begins to flex and continues to do so until the foot is flat on the ground. A typical magnitude of this flexion is 15 degrees. Just before the middle of the period of full weight bearing, the knee joint once more passes into extension, which is immediately followed by the terminal flexion of the knee. This begins simultaneously with heel rise, as the limb is carried into swing phase. During this period of stance phase, occupying about 40% of the cycle, the knee is first extended, then flexed, and again extended before its final flexion.

During the beginning and end of the stance phase, knee flexion contributes to smoothing the abrupt changes at the intersections of the arcs of translation of the center of mass (Fig. 1-6).

These three elements of gait—pelvic rotation, pelvic list, and knee flexion during early stance phase, all act in the same direction by flattening the arc through which the center of mass of the body is translated. The first (pelvic rotation) elevates the ends of the arc, and the second and third (pelvic list and knee flexion) depress its summit. The net

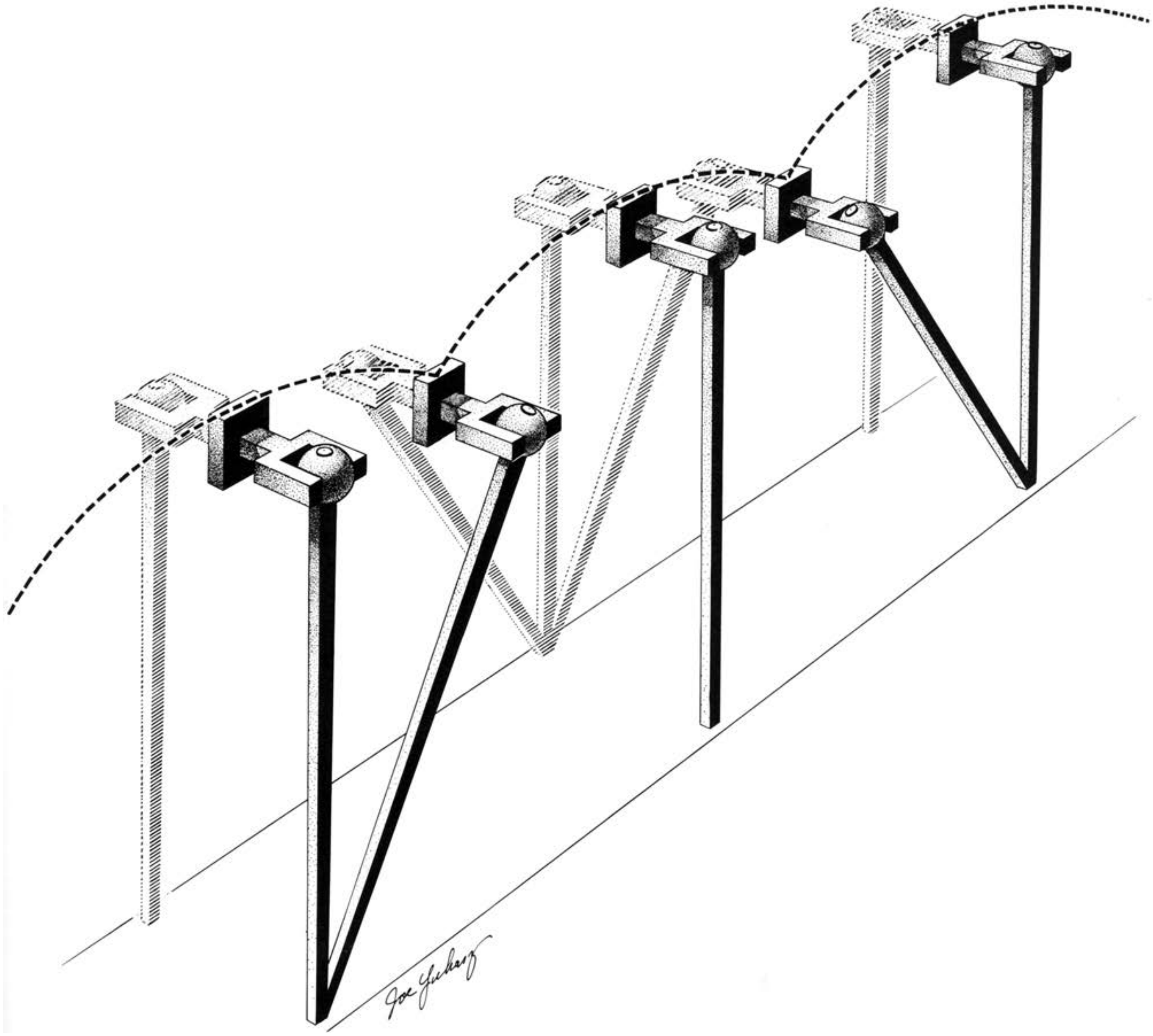

FIGURE 1-3. Simplified model depicting bipedal locomotion. The pelvis is a double-forked bar articulating with spheres depicting the hip joints and carrying a small block that represents the center of mass of the body. The legs are straight members without knee, ankle, or foot components. Note that the pathway of the center of mass is through a series of intersecting arcs. (From Saunders JB, Inman VT, Eberhart HD. The major determinants in normal and pathological gait. *J Bone Joint Surg* 1953; 35–A:543.)

effect is the passage of the center of mass through a segment of a circle, the radius of which is about 2.2 times longer than the length of the lower limb. The effective lengthening of the limbs reduces materially the range of flexion and extension at the hip joint required to maintain the same length of stride.

The three elements so far discussed (pelvic rotation, pelvic list, and knee flexion) act to decrease the magnitude of the vertical displacement of the center of mass of the body. However, if no additional elements were active, the pathway of the center of mass would still consist of a series of arcs, and at their intersections the center of mass would be subject to a sudden change in vertical displacement. This would result in a jarring effect on the body. Thus, an additional mechanism must be active that smooths the pathway of the center of mass by a gradual change in the vertical displacement of the center of mass from a downward to an upward direction, converting what would be a

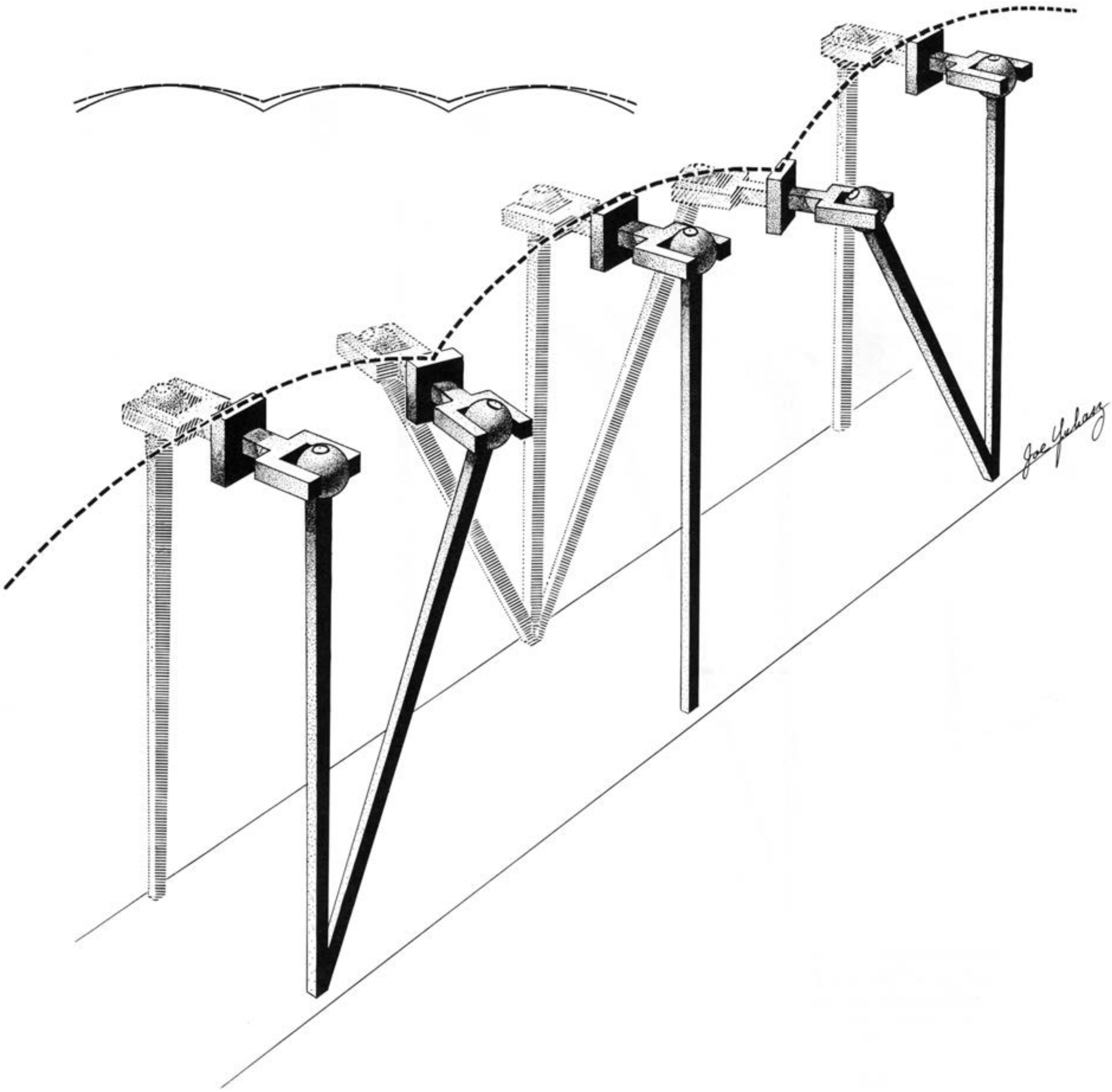

FIGURE 1-4. Effect of pelvic rotation. By permitting the pelvis to rotate in a horizontal plane during locomotion, the center of mass is prevented from falling as far during the phase of double weight bearing as was shown in Figure 1-3. The solid line at the top represents the curve shown Figure 1-3. (Adapted from Saunders JB, Inman VT, Eberhart HD. The major determinants in normal and pathological gait. *J Bone Joint Surg* 1953;35–A:543.)

series of intersecting arcs into a sinusoidal path. This is accomplished by certain movements in the knee, ankle, and foot.

The single most important factor in achieving the conversion of the pathway of the center of mass from a series of intersecting arcs to a smooth curve is the presence of a foot attached to the distal end of the limb. Through its action, the foot enables the pathway of displacement of the knee to remain relatively horizontal during the entire stance phase. This in turn allows the initial knee flexion to act more effectively in smoothing the pathway of the hip. To understand the mechanics involved, a series of simple drawings may be helpful. In Figure 1-7, the actual pathway of the knee joint during stance phase is shown. Except for an initial rise, the pathway is relatively flat. In Figure 1-8, three other situations are shown. If no foot is attached to the shank, the pathway of the knee is an arc whose radius is the distance from the floor to the knee. By simply