Determinants of Gait

There is no unique way to describe the motions of the limbs during walking, but one description, given in 1953 by Saunders, Inman, and Eberhart, is useful because of its simplicity and its completeness. In this description, six determinants of normal gait are distinguished. Each determinant generally depends on a single degree of freedom in one of the joints.

Fig. 8.3. (Continued)

Fig. 8.4. Compass gait. The stance leg remains stiff at all times, and the trunk moves in an arc in each step. From Inman, Ralston, and Todd (1981). Originally published in slightly different form in Saunders et al. (1953).
**Compass gait.** In fig. 8.4, the only motions of the lower extremities permitted are flexions and extensions of the hips. The pelvis moves through a series of arcs, where the radius of the arc is determined by the leg length. This is called *compass gait*.

**Pelvic rotation.** The next stage of complexity, shown in fig. 8.5, allows rotary motion of the pelvis about a vertical axis. The amplitude of this motion is about ±3 degrees in walking at normal speeds, but increases at high speeds (Saunders et al., 1953). The effectively greater length of the leg when pelvic rotation is utilized is responsible for a longer step length and a greater radius for the arcs of the hip, hence a smoother ride. Walking racers use a walking

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**Fig. 8.5.** In pelvic rotation, the pelvis turns about a vertical axis, lengthening the step and flattening the arcs by increasing the effective length of the leg. From Inman, Ralston, and Todd (1981). Originally published in slightly different form in Saunders et al. (1953).

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...style which depends on exaggerated pelvic rotation. In this way, they are able to delay the transition from walking to running at high speeds.

**Pelvic tilt.** When the pelvis is allowed to tilt, so that the hip on the swing side falls lower than the hip on the stance side, the arcs specifying the trajectory of the center of the pelvis are made still flatter (fig. 8.6). As shown in the figure, the lowering of the swing hip occurs rather abruptly at the end of the double support phase, just before toe-off of the swing leg. The swing hip then rises slowly through the remainder of the swing period. Notice that the

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**Fig. 8.6.** Adding pelvic tilt to pelvic rotation flattens the arcs further. Just before toe-off, the pelvis is lowered abruptly on the swing leg side, then raised slowly until heel strike. From Inman, Ralston, and Todd (1981). Originally published in slightly different form in Saunders et al. (1953).
introduction of this determinant necessarily also brings in the requirement for knee flexion of the swing leg. Otherwise, with the swing hip lower than the stance hip, the foot of the swing leg would strike the ground as it moved forward.

**Stance leg knee flexion.** In fig. 8.7, flexion of the stance leg has been added to the determinants listed so far. The effect has been to flatten further the arcs traced out by the center of the pelvis.

**Plantar flexion of the stance ankle.** To smooth the transition from the double support phase to the swing phase, the ankle of the stance leg plantar flexes (sole, or plantar surface of the foot, moves down) just before toe-off (fig. 8.8). This motion also plays an important part in establishing the initial velocities of the shank and thigh for the subsequent swinging motion.

**Lateral displacement of the pelvis.** Because weight bearing is alternately transferred from one limb to the other, and because there is a finite lateral separation between the lower limbs, the body rocks from side to side somewhat during walking. The frequency of this lateral motion is half the frequency of the vertical excursions of the pelvis (fig. 8.9).

There is a bipedal toy which walks down shallow grades by making lateral rocking motions synchronized with the swinging of its pendulum legs (fig. 8.9, inset). As the toy rocks to the left, the right leg is free to swing forward, and therefore it arrives in the correct position to catch the weight as the toy rolls back to the right. The energy needed to overcome friction is supplied by the fact that the toy steps down a bit with each step forward.

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**Fig. 8.7.** Knee flexion of the stance leg is added to pelvic rotation and pelvic tilt. From Inman, Ralston, and Todd (1981). Originally published in slightly different form in Saunders et al. (1953).

**Fig. 8.8.** Ankle plantar flexion of the stance leg is added to knee flexion. Most of the plantar flexion occurs just before toe-off. From Inman, Ralston, and Todd (1981). Originally published in slightly different form in Saunders et al. (1953).

**Fig. 8.9.** Lateral displacement of the pelvis, a sinusoidal motion at half the frequency of the up-and-down motions. Inset: Walking toy, which moves down shallow inclines by a complex motion which includes lateral rocking and pendular swinging of the legs. The legs are fastened to the body by an axle, as shown. Main figure from Inman, Ralston, and Todd (1981). Originally published in slightly different form in Saunders et al. (1953).
The frequency of the lateral motions of the walking toy is strongly amplitude dependent. As the amplitude of the lateral rocking decreases, the frequency increases. A penny which has been spinning on a table top and is finally coming to rest shows this same behavior—it makes a higher and higher pitched sound just before it lies flat. The walking toy lowers its cadence as it walks faster down steep slopes—and this is just the opposite of what can be observed in human walking, where a faster speed leads to a somewhat higher stepping frequency. Nevertheless, human walking has quite a lot to do with the motions of a pendulum, as we shall see.

**Ballistic Walking**

Electromyographic records using electrodes in the leg muscles show that there is very little activity in the swing leg during walking at normal speed, except at the beginning and the end of the swing phase (Basmajian, 1976). The muscles are active during the double support period, when the initial conditions on the angles and velocities of each of the limb segments are being established. Thereafter, the muscles all but turn off and allow the leg to swing through like a jointed pendulum.

A theory for walking based on these observations may be called a **ballistic walking** model, because, like a projectile moving through space, such a model moves entirely under the action of gravity, once it begins its swing.

**Defining the model.** A schematic diagram of the ballistic walking model is shown in fig. 8.10. It consists of three links, one for the stance leg and one for each for the thigh and shank of the swing leg. The foot of the swing leg is attached rigidly to the shank at right angles. The stance foot may be ignored, since it remains planted on the ground. The mass of the trunk and upper part of the body is lumped at the hip joint, but the masses of the lower limb segments are distributed in a realistic way. The equations of motion for this system are derived (most conveniently using Lagrange's equations) and programmed on a computer. Arbitrary initial conditions are chosen for the angles and velocities of the leg, thigh, and shank with respect to the vertical, subject to the condition that the toe of the swing leg must leave the ground just as the swing starts. Then the equations are solved, taking small forward increments in time, until the heel of the swing leg strikes the ground. This establishes the duration of the swing period, during which the model moves from configuration 2 to configuration 3 in fig. 8.10. By trial and error, the set of initial conditions on the angular velocities of the thigh and shank is determined for each step length, \( s_L \) (for walking, step length is the distance between heel strikes). A correct choice of initial conditions just permits the swing leg knee to come to full extension at the moment the heel strikes the ground. If the choice of initial velocities has been incorrect, the knee locks before heel strike. Another condition requires that the toe of the swing leg must not strike the ground during mid-swing.

**Results of the ballistic model.** This last condition turns out to be very important in determining the kinematics of ballistic walking. In fig. 8.11, the calculated range of times of swing \( T_S \), is shown as a function of the normalized step length, \( S_L = s_L/\ell \), where \( \ell \) is the leg length. Here \( T_S = T/T_w \) where \( T \) is the swing time in seconds and \( T_w \) is the natural half-period of the leg as a rigid pendulum, \( T_w = \pi (I/\ell m g Z)^{1/2} \), with \( I \) = moment of inertia of the rigid leg about the hip, and \( Z \) defined as the distance of the leg's center of mass from the hip. For a leg length of 1.0 m, \( T_S \) is approximately 0.82 sec.

The line \( B \) indicates the boundary between those steps (to the left of the line) in which the toe of the swing leg strikes the ground during some intermediate phase of the swing period, and those steps (to the right) in which it clears the ground. By comparison, the line \( A \) in the figure shows the boundary determined by the requirement that the vertical force shall always remain positive. Combinations of \( S_L \) and \( T_S \), to the left of line \( A \), correspond to a swing phase so rapid that the model flies off the ground. An inverted pendulum has this same behavior—its weight will be negative when \( \nu^2/g \ell \) is greater than or equal to 1.0, where \( \nu \) is the velocity of the pendulum at the top of its swing (inset, fig. 8.11). The point is that line \( B \) lies to the right of line \( A \), and therefore constitutes the minimum swing time boundary for ballistic.


References


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