

Control of the medial-lateral balance in walking

Eleven normal adults had their gait tested from the viewpoint of ground reaction force, myoelectric activity, and the motion of pronation-supination in the foot. There were marked differences in the myoelectric activity between the large lateral component force and the smaller one during the midstance phase. When the lateral component force was large, the pronation of the foot was small; the peroneus longus was active during the midstance phase; and the activity of the tibialis posterior disappeared earlier than in the small component. On the other hand, when the lateral component force was small, the pronation was large; the tibialis posterior, flexor digitorum longus, and extensor hallucis longus were all active; but the peroneus longus remained inactive during the midstance phase. Based on these findings, it is suggested that the leg muscles and the motion of the foot take part in controlling the medial lateral balance in walking.

Nobuo Matsusaka

Department of Orthopedics,
Nagasaki University School
of Medicine, 7-1, Sakamoto-
machi, Nagasaki 852, Japan

In the human gait the center of gravity of the body is displaced to the supporting side at every step (Saunders et al. 1953, Bower & Hall 1975, Morris 1977), and the foot that steps forward must control the medial-lateral oscillation of the body caused by the thrust of the push-off leg (Ducroquet et al. 1968). The body balance in the frontal plane is somewhat unstable as shown in the variety of the lateral components of the ground reaction force, but it is very important to control the medial-lateral balance in order to perform a smooth forward movement.

Arthrodesis of the subtalar joint may relieve pain, but most patients who have a fused subtalar joint often complain of difficulty in controlling their body balance during walking on uneven ground (Fogel et al. 1982, Johansson et al. 1982). It is thought from their complaints that the subtalar joint takes part in body control during walking.

We have studied how the balance of the body is controlled from the viewpoint of ground reaction force, myoelectric activity, and the motion of pronation-supination in the foot.

Subjects and methods

Eleven normal, 20-29-year-old male volunteers were enlisted for this study. The subjects were asked to walk on a walkway in 30 to 50 trials at each subject's chosen comfortable speed. Chosen speed, cadence,

and step length for each subject were measured. The ground reaction forces, the angular changes of pronation and supination in the foot, electromyographic signals, and foot switch signal were recorded simultaneously.

The ground reaction forces were determined using a Matake (1976) force plate, embedded in the center of the walkway. The vertical, forward-backward, and lateral components were recorded.

Electromyograms were obtained for each of the eight muscles under observation. The myoelectric activity of the paravertebral muscle, gluteus medius, and peroneus longus were recorded using surface electrodes placed over the muscle belly, and the activity of the tibialis posterior, extensor hallucis

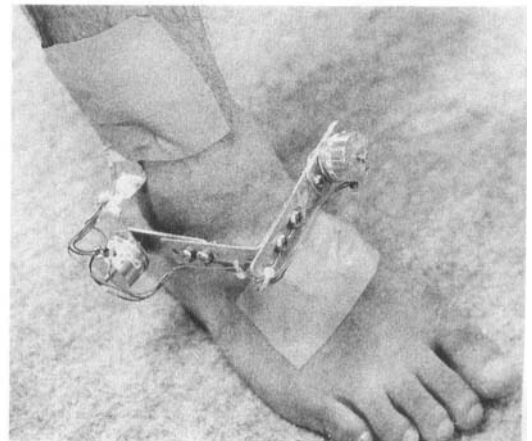


Figure 1. Electrogoniometer to measure the angular changes of pronation-supination in the foot.

longus, flexor hallucis longus, extensor digitorum longus, and flexor digitorum longus were recorded using intramuscular 70 μ m fine-wire electrodes with the Goodgold (1974) method of insertion. The position of each electrode was tested by electric stimulation of the muscle through the fine wire inserted prior to the experiment. The electromyographic recordings were transmitted by two 4-channel telemeters (NEC SAN-EI Co., Tokyo, Japan), which were attached to a belt worn around the subject's waist. The raw electromyographic recordings were transformed into linear envelopes, which were produced by a detector (NIHON KODEN Co., Tokyo, Japan) with a time constant of 90 ms.

The angular changes of pronation and supination in the foot were measured by electrogoniometer using a potentiometer. The axis of the potentiometer was made to coincide with that of the subtalar joint, which was approximately 40° in the sagittal plane and 20° in the horizontal plane (Manter 1941, Inman 1976, Langelaan 1983). However, there is a great range of individual variation (Inman 1976); therefore, the axis of mechanical and anatomic joints coincided until subjects felt no interference with their normal motions (Wright et al. 1964). For this study, the electrogoniometer was attached to the lower leg and foot with an adhesive agent and tape (Figure 1).

Lead contacts were attached to the sole of the foot, the heel, the 1st and 5th metatarsal heads, and the big toe. The foot switch signals in the stance phase were divided into seven phases (T1 to T7) by the positional situation of sole contact (Figure 2). Wires from the contacts and electrogoniometer were carried by an overhead track to the recording equipment. The force plate was covered with copper sheeting to complete the circuits for the four contacts.

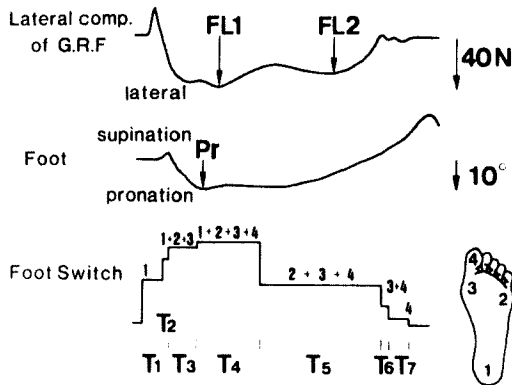


Figure 2. Points of measurement. G. R. F.: ground reaction force. FL1: maximum amplitude of the lateral component force in the phase of acceleration. Pr: maximum pronation of the foot in the early stance phase.

The activity of the paravertebral muscle, gluteus medius, flexor hallucis longus, and extensor digitorum longus showed the same pattern both within and between subjects. However, there were step-to-step variations in the patterns of activity of the peroneus longus, tibialis posterior, flexor digitorum longus, and extensor hallucis longus; each pattern of activity of these muscles was mainly classified into two types. The activity of the peroneus longus appeared from the early period of the stance phase (Type A), or after heel-off (Type a). The tibialis posterior was active in the early stance phase (Type B) or from the early period of the stance phase to the latter half of the stance phase (Type b). The flexor digitorum longus acted after heel-off (Type C) or from the early period of the stance phase (type c), and the extensor hallucis longus was rarely active from T3 to T4 (Type D) or was even active from T3 to T4 (type d).

In all the subjects, the patterns of activity of these muscles were divided into the above-mentioned types. The variation in the activity patterns seemed to be related to the amplitude of the lateral component of the ground reaction force. For these reasons, the relationship between the lateral component forces and the patterns of muscular activity was investigated in each subject.

The maximum amplitudes of the lateral component in the phase of deceleration and that of acceleration were termed FL1 and FL2, respectively, and the maximum pronation of the foot in the early stance phase was named Pr (Figure 2). The relationship between FL1 and FL2 was investigated to make clear whether FL2 was influenced by FL1. The correlation between FL1 and Pr, and between FL1 and T4 was also investigated to explain the relationship between the lateral component forces, the angular changes of the foot, and the positional situation of sole contact.

A *t* test was applied to the correlation coefficients. The significance level used was $P < 0.05$.

Results

The mean walking speed, cadence, and step length of all subjects were 0.99 ± 0.05 m/s, 93 ± 0.9 steps/min, and 0.64 ± 0.26 m (mean \pm SD), respectively.

There was rapid pronation of the foot just after heel contact, followed by progressive supination until toe-off (Figure 3). In the correlation of the lateral component forces, the angular changes of the foot and the patterns of the foot switch signal, there was a positive correlation between the maximum amplitudes of

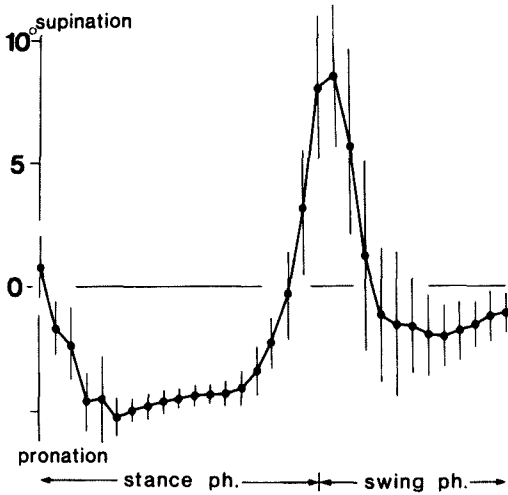


Figure 3. Mean angular changes of pronation-supination in the foot in a normal subject. The dots and bars represent means and standard deviations, respectively.

the lateral component in deceleration (FL1) and acceleration (FL2) in 10 of 11 subjects. There was a negative correlation between FL1 and stance phase 4 (T4) in 9 of 11 subjects. Moreover, we found a correlation between FL1 and the maximal pronation in the early stance phase (Pr) in 10 of 11 subjects.

In all the subjects the patterns of the activity of the peroneus longus, tibialis posterior, flexor digitorum longus, and extensor hallucis longus belonged to Types A, B, C, and D, respectively, when the amplitudes of the lateral components

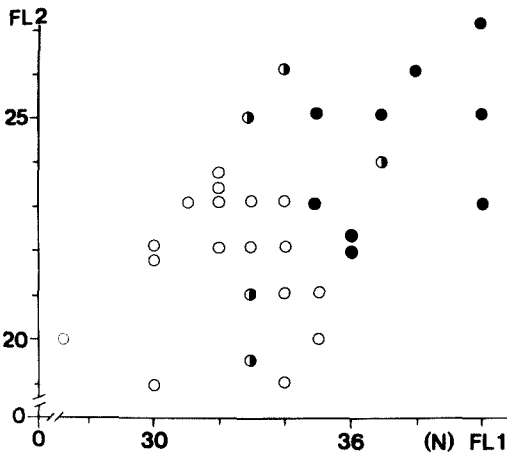


Figure 4. Relationship between the lateral component force and the patterns of muscular activity of the peroneus longus. ●: Type A, ○: Type a, ◐: intermediate type.

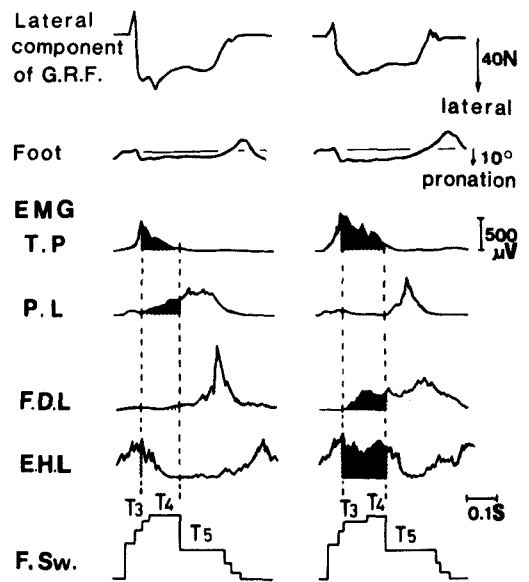


Figure 5. Difference in myoelectric activity and the angular changes of pronation-supination of the foot between the large lateral component force and the smaller one. G.R.F.: ground reaction force, T.P.: tibialis posterior, P. L.: peroneus longus, F.D.L.: flexor digitorum longus, E.H.L.: extensor hallucis longus, F.sw.: foot switch signal.

(FL1 and FL2) were larger. On the other hand, the patterns of muscular activity belonged to Types a, b, c, and d, respectively, when FL1 was smaller (Figure 4).

There were marked differences in myoelectric activity between the large lateral component force and the smaller one during the period from T3 to T4 (Figure 5). With some subjects, there were various proportions in the activity patterns of these muscles. Types A and a of the peroneus longus ranged from 27 to 63 per cent and from 18 to 61 per cent, respectively; Types B and b of the tibialis posterior, from 28 to 57 per cent and from 28 to 52 per cent, respectively; Types C and c of the flexor digitorum longus, from 20 to 41 per cent and from 35 to 57 per cent, respectively; and Types D and d of the extensor hallucis longus, from 22 to 36 per cent and from 43 to 60 per cent, respectively.

In all the subjects when the lateral component force was larger, the pronation of the foot was smaller. The peroneus longus was active during the period from T3 to T4, and the activity of the tibialis posterior disappeared

earlier than in the smaller component. On the other hand, when the lateral component force was smaller, the pronation was larger; the tibialis posterior, flexor digitorum longus, and extensor hallucis longus were all active, but the peroneus longus remained inactive during this period.

Discussion

The pattern of the angular changes of pronation-supination in the foot was similar to that of previous studies (Wright et al. 1964, Fogel et al. 1982). Theoretically, this pattern of angular changes is the subtalar motion in walking because the axis of the goniometer was made to coincide with that of the subtalar joint. When the foot is fixed on the ground, plantar flexion and dorsiflexion in the talocrural joint produce internal rotation of the leg because of the obliquity of the talocrural axis (Inman & Mann 1978). The goniometer, therefore, recorded motion not only in the subtalar joint, but also in the talocrural joint, i.e., the motion of pronation-supination in the foot.

In myoelectric activity, there were marked differences between the large lateral component force and the smaller one during the midstance phase of walking in all the subjects. When the lateral component force was smaller, the pronation of the foot was larger. The tibialis posterior, flexor digitorum longus, and extensor hallucis longus were active during this period (Figure 5). We suggest that the tibialis posterior and flexor digitorum longus were active throughout this period in order to prevent the lateral inclination of the lower leg over the fixed foot. The subtalar joint has been likened to a "mitered hinge" connecting the leg to the foot (Wright et al. 1964, Inman 1976) because the movement is a rotatory one about a single oblique axis. Longitudinal rotation of the leg imposes a longitudinal rotation of the foot (pronation-supination). Internal rotation of the leg during the early stance phase causes pronation of the foot and a consequent elevation of the lateral side of the foot and depression of the medial side of the foot (Mann 1975, Inman

1976). It is thought, therefore, that the flexor digitorum longus and extensor hallucis longus were active during the midstance phase in order to allow the foot to adapt to the ground.

On the other hand, when the lateral component force was larger, the pronation of the foot was smaller. The peroneus longus was active during the midstance phase, and the activity of the tibialis posterior disappeared earlier than in the smaller component. It is suggested that the peroneus longus must be active during the midstance phase so as to prevent the medial inclination of the lower leg over the fixed foot. Moreover, it is thought that the peroneus longus acts to hold the head of the first metatarsal because this muscle inserts at the first metatarsal.

The muscles comprising the hip abductor, pelvic balancer, and torso supporter groups were active during the midstance phase, but showed the same patterns both within and between subjects. The actions of the hip abductor and torso balancers are a minimum requirement to maintain bipedal walking. However, the peroneus longus, tibialis posterior, flexor digitorum longus, and extensor hallucis longus, in the muscular patterns that changed with the amplitude of the lateral component force and the amount of pronation of the foot, act in response to extrinsic forces, such as kinetic force of the body, gravity, and ground reaction. It is suggested that the lower leg muscles take part in controlling the medial-lateral balance in walking together with the motion of the foot.

It is interesting that there were various proportions in the patterns of muscular activity of the peroneus longus, tibialis posterior, flexor digitorum longus, and extensor hallucis longus among the subjects. From these various proportions, it can be assumed which pattern of walking was used by each subject.

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