Physiol. Res. 43: 371−377, 1994

The Contribution of Foot Deformation to the Changes of Muscular Length and Angle in the Ankle Joint During Standing in Man

V.S. GURFINKEL, YU.P. IVANENKO, YU.S. LEVIK

Institute of Information Transmission Problems, Russian Academy of Sciences, Moscow

Received January 27, 1994
Accepted September 20, 1994

Summary

This study was designed to evaluate the extent of foot deformation in healthy subjects during standing on an immobile support and during slow tilts of the support platform by 1 deg. The angle in ankle joint was evaluated by two methods: as an angle of shin inclination relative to the platform and as an angle, calculated on the basis of recording of the projective length of the soleus muscle. It was shown that the real changes of the angle in ankle joint during standing on an immobile platform were up to 2 times smaller than the changes of angular position of the shin relative to vertical axis. However, considerable intersubject variability was observed in this respect. During slow tilts of the support platform a marked divergence was observed in the shape of recordings of two "ankle angles" in subjects with high foot compliance. The vertical displacements of the calcaneus recorded by means of a clamp rigidly fixed at the heel were 0.5 ± 0.3 mm (the range $0.1-1$ mm) for each degree of body deviation in the forward or backward direction. In 12 subjects, the average foot compliance was 0.04 ± 0.03 deg/Nm (maximal value 0.1 deg/Nm). It can be assumed that the mechanical properties of the foot can appreciably influence the afferent outflow during maintenance of orthograde posture in man.

Key words

Foot deformation − Muscle length − Ankle joint − Orthograde posture − Man

Introduction

By its structure and function the foot can be defined as a specialized part of the skeleto-motor system adapted to direct interaction with a support surface (Arcan and Brull 1976). At the same time, the foot represents an important receptive field, formed by numerous skin, joint, tendon and muscular receptors. Experimental data (Lisin *et al.* 1973, Prochazka *et al.* 1978, Popov *et al.* 1981, Burke *et al.* 1991, Dietz *et al.* 1993, Lipshits 1993, Fox and Ponsford 1993) permit to assume that information about support reactions coming from this receptive field plays an important role in the control of posture and movement. However, when investigating the maintenance of orthograde posture in man, the foot is usually treated as an absolutely rigid non-deformable link, and the ankle joint as an ideal hinge with one degree of freedom. Under these conditions, the changes of length of ankle joint muscles are unequivocally determined by the change of ankle angle which is measured simply as an angle of shin inclination relative to the support surface. These assumptions form the basis of numerous models of postural control (Nashner and McCollum 1985), of calculations of perception thresholds of the ankle angle changes during standing (Popov *et al.* 1982), of the estimates attempting to determine if the length changes during easy standing exceed the limits of action of short-range stiffness (Gurfinkel *et al.* 1974) or of the estimates of the importance of tendon compliance (Rack *et al.* 1983, Proske and Morgan 1987). Nevertheless, it seemed worthwhile to investigate to what extent these idealized descriptions of the foot and ankle joint correspond to reality. It is clear that foot deformation would give rise to two effects. First of all, the muscle length would not be determined exactly by the joint angle, and secondly, the signals from joint receptors would not provide any longer a precise measure of the shin angle relative to the vertical axis.

One could object that these effects could be neglected because of the small compliance of the foot. Nevertheless, the extent of deformations could turn out not to be so negligible when taking into account the large body weight and, consequently, a large load on the feet. Besides, the spontaneous body oscillations during easy standing themselves do not exceed a fraction of a degree. So even a small deformation could yield relatively large errors in the measured changes of ankle angle. Thus, the present study was designed to evaluate the foot compliance during easy standing or small perturbations of the support surface and to estimate the contribution of this compliance to the length changes of the soleus muscle.

Methods

The experimental apparatus consisted of a stabilographic platform installed on a seesaw (Fig. 1). The lower part of the seesaw was curved in the form of a circular sector with a radius of 25 cm. An electromechanical actuator connected with the seesaw through the lever could tilt it forwards or backwards. This produced a corresponding inclination of the subject's body in the sagittal plane. The rigidity of the actuator-platform system was about 250 Nm/deg, which is sufficiently high. The subject stood on the platform wearing spectacles with milk glasses. The ear-phones on the head of the subject prevented him from hearing the moment when the actuator was turned on. For trials on the immobile support, the stabilographic platform was installed directly on the floor.

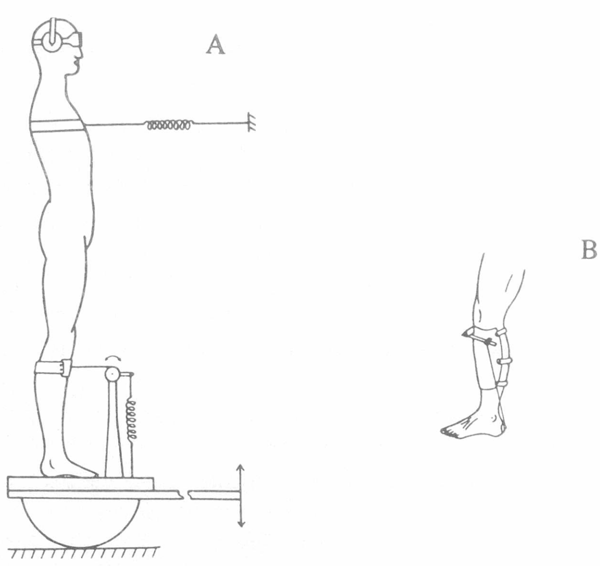

Fig. 1
The schematic view of the experimental set-up (A) and the scheme of the measurement of projective length of the soleus muscle (B).

Body sway in the sagittal plane was induced by a slow linear ramp of the support platform. The following parameters of perturbation were used: the velocity of platform tilt ±0.04 deg/s, amplitude 1 deg, record duration – 100 s; the ramp started on the 31st second. The subject was instructed to stand easy without conscious interference with postural control. This test was repeated 8 times in each subject.

In another type of experiment, body sway was obtained by voluntary forward and backward body inclination. The subject was instructed to perform these tilts slowly, exclusively by motion in the ankle joints.

In a series of experiments, body deviation and therefore the redistribution of foot pressure was obtained by voluntary flexion and extension in the hip joint. The subject maintained a constant angle of shin inclination during this test using visual feedback by observing an oscilloscope screen.

In each experiment the sagittal stabilogram, body sway, angle of platform rotation and angle in the ankle joint were simultaneously recorded. In some trials the vertical shift of the calcaneus was additionally evaluated (distance h in Fig. 2B). For this purpose, the clamp was rigidly fixed to the heel or, alternatively, an adhesive plate was glued to the skin over the tuberosity of the calcaneus 3–4 cm above the surface of the platform. The vertical displacement of the clamp or the plate relative to the platform surface was measured with a special strain gauge sensor. All signals were fed into an IBM PC AT computer with analog-to-digital converter for subsequent processing. The sampling rate for the mechanograms was 5/s.

The angle of platform rotation was measured by a strain gauge sensor. Displacements of the subject's centre of gravity in the sagittal plane were recorded by a stabilographic platform (Gurfinkel 1974), rigidly fixed to the top of the seesaw. For this purpose, the change of the torque in the ankle joint (sagittal stabilogram) was divided by the weight of the subject. The displacements of the upper part of the body in the antero-posterior direction were measured by a strain-gauge connected by an elastic band to the "breast point" (point on the midline of the sternum at the level of the inter-axillary line (Fig. 1). The tension and stiffness of the elastic band were very small (0.75 N and 7.5 N/m, respectively) and did not influence the subject's posture. The signal of "breast point" movement was corrected for the shifts due to the movement of the seesaw over the floor. Corrected values of the "breast point" shift were converted to an angle of rotation of the line connecting the "breast point" with the axis of the ankle joint relative to the vertical axis (body sway).

Changes of the ankle angle were measured by two methods: as an angle of shin inclination and as an angle calculated on the basis of direct recording of the projected length of the soleus muscle. We selected the soleus muscle as it is a one-joint muscle, so its length can be easily converted to the angular change of the ankle. The soleus muscle is also the most active muscle in the ankle joint during standing. Both sensors of ankle angle were fixed on the left leg. The angle of shin inclination was measured as follows. A plastic groove (see below), curved in accordance with contour of the shin cross-section was attached to the shin. This groove was tightly bandaged to the shin with a rubber band so that it rested with its flat part on the planum tibiae. The groove was connected by a nonelastic string to a potentiometer, placed on the metal support, fixed to the platform in front of the subject's left leg. In this way the inclination of the shin produced a distortion of the potentiometer. The returning force was provided by the weak spring.

For evaluation of the actual changes of muscle length (and the real changes of ankle angle) the distance between two points was measured (Fig. 1B). An adhesive plate 2.5 x 3.0 cm with a small metal knob was fixed on the skin over the point of insertion of the Achilles tendon on the calcaneus. A nonelastic thread was attached to this knob. The other end of the thread was attached to a compliant strain gauge mounted on an individually adjusted groove made of orthopaedic "polivik" plastic easily deformable after heating in hot water. The point of attachment of the thread to the strain gauge roughly corresponded to the projection of the proximal origin of the soleus muscle in the lateral plane: about 5 cm below the knee joint and immediately behind the posterior edge of the tibiae. The stiffness of the strain gauge was small (0.02 N/mm) so that the thread tension could not lead to appreciable skin deformation in the distal insertion point. Thus the signal measured was proportional to changes of the muscle soleus length during standing. Knowing the initial geometry of the thread attachment points relative to the axis of ankle joint (assumed to pass through the medial malleolus) for each subject, one could easily convert the measured change of muscle length to an angle change in the ankle joint.

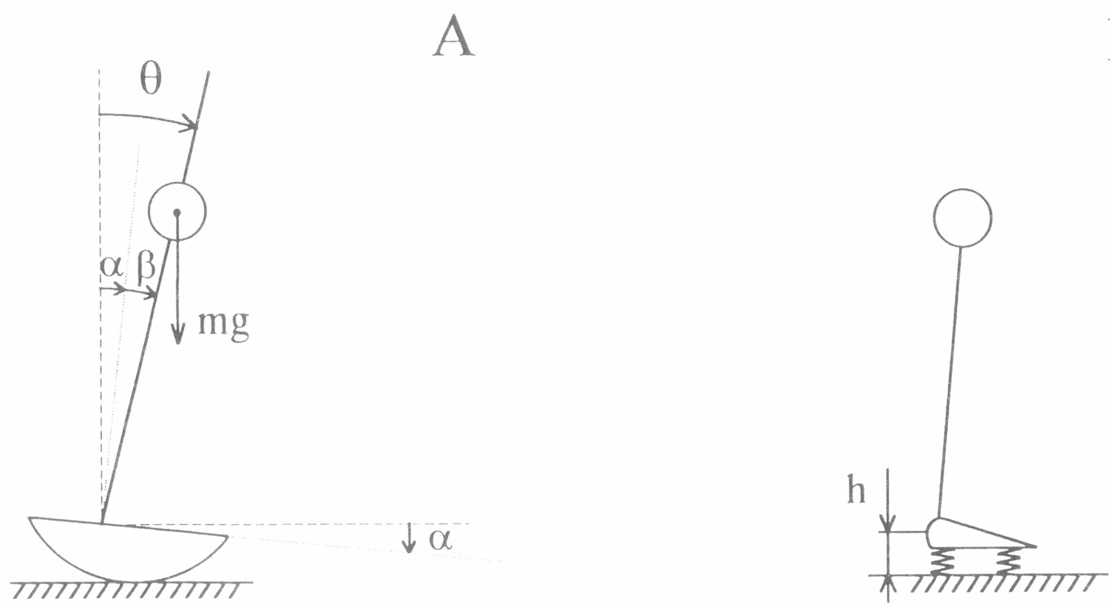

Fig. 2.
The model of a subject standing on the platform (A) and a schematic representation of "sagittal" foot stiffness (B). θ – the angle of trunk inclination relative to vertical, α – the angle of platform turn, β – the angle of shin inclination relative to platform surface, h – the height of the referent "heel point" over the ground. The positive direction for all angles was assumed to be that producing forward body motion (clockwise in this figure).

The main source of error during the conversion of the soleus length changes to changes of the ankle angle was due to inaccuracy in the determination of the ankle joint axis (about 0.5–1 cm). Therefore, the accuracy of angle estimation by measurement of muscle length was about 15 %. This method is also sensitive to the redistribution of body weight between the right and left leg. Thus the signal of muscle length can be modified by tilting the body in the frontal plane.

Thus, in our experiments, we could compare in the same units (degrees) four recorded signals: the angle of platform displacement, the body sway, the angle of shin inclination relative to the platform and the angle in the ankle joint calculated from the distance between the insertion points of the soleus muscle. If during easy stance the body oscillates as a whole, i.e. that all its mobility is concentrated only in the ankle joint (Fig. 2A), then the angle of body inclination equals the sum of the angle of platform displacement and angle of shin inclination:

$$\theta = \alpha + \beta \quad (1)$$

Twelve healthy subjects including the authors (5 women and 7 men, from 20 to 70 years of age) participated in these simple and non-invasive experiments. All quantitative data are given as means ± S.D.

Results

1. Changes of the ankle joint angle during easy standing and during voluntary body tilts

Small irregular body oscillations (usually not exceeding about 0.5 deg) always take place during easy standing on an unmoving platform. They reflect the continuous process of postural regulation. Voluntary body tilts were also rather small (about 1–2 deg). Thus, under our experimental conditions, the maximal displacements of the common centre of gravity of the subject were small (range 0.7–3.0 cm), that is apparently in the range of the stable equilibrium. A loss of contact of heels or toes with the platform surface was never observed, and the change of projective length of the soleus muscle and the vertical displacement of the calcaneus were always gradual and not stepwise.

The direct recording of the projective length of the soleus by means of measuring the distance between its insertion points has shown that, in 5 out of 12 subjects studied, the real changes of the ankle angle during voluntary body tilts on an immobile platform were by more than 25 % smaller than corresponding changes of shin orientation or body sway that significantly exceeded the methodical error (about 15 % as indicated in the Methods). In three of these five subjects the difference was approximately twofold. It can be concluded that the rest of body rotation relative to the vertical plane is accounted by the deformation of the soft tissues of the foot (Fig. 2B).

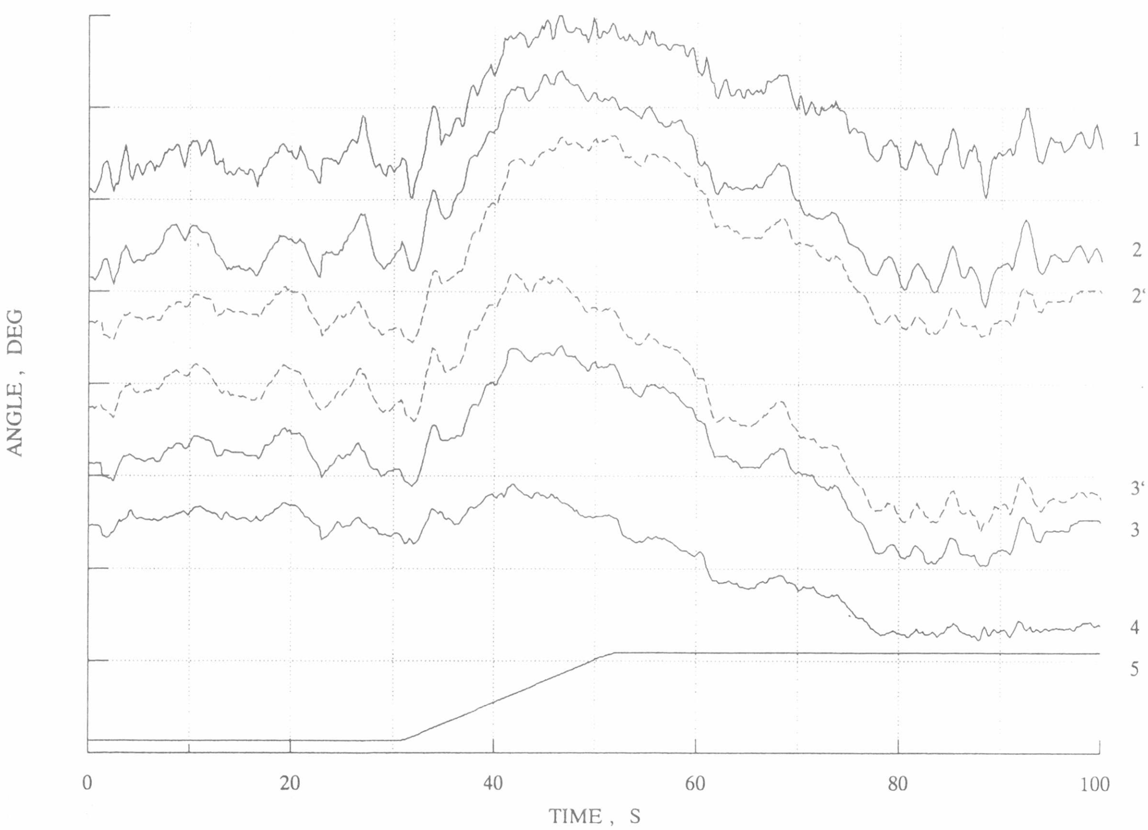

Fig. 3
The postural response on the slow one-degree forward platform turn. 1 – stabilogram; 2 – the angle of body inclination, 2' – the angle of body inclination estimated as the sum of curves 3 and 5 (formula 1); 3 – the angle of shin inclination, 3' – the angle of shin inclination obtained from curves 4 and 2 (formula 2); 4 – the ankle angle calculated on the basis of the changes of projective length of the soleus muscle; 5 – the angle of platform turn. One scale division corresponds to 10 Nm for curve 1 and to 1 deg for curves 2–5.

2. The behaviour of the ankle joint angle during slow platform tilts

During the slow platform tilt the body behaved almost as an inverted pendulum. Thus the satisfactory approximation of the curve of the body displacement could be obtained by summing up current values of the platform turn angle and the ankle angle according to formula (1). The discrepancy between the calculated and the actual values of body sway usually did not exceed 0.5 deg (Fig. 3, curves 2 and 2'). It can thus be concluded that even if the body does not move as a single whole, the rotation in the knee and hip joints is not very large and mobility is concentrated mostly in the ankle joints. The body response to the slow platform tilt by 1 deg passed through two different phases (Fig. 3). initially, the body inclined in the same direction by 0.5–2 deg (depending on the subject). When the platform motion terminated or just before it, the change of ankle angle in the opposite direction started. This later phase of the gradual approach of the body position and the ankle angle to a stationary level lasted for 10–25 s (mean 18 s).

In some subjects, more prominent (than at relaxed standing) body deviation during the slow platform tilt by 1 deg did not only lead to a quantitative difference of two "ankle angles" but also to marked differences in the form of the curves (Fig. 3). Because of the simultaneous motion of the centre of gravity (resulting in a redistribution of pressure and foot deformation), the initial change of ankle joint was less than the change of the angle of shin inclination relative to the platform, and the maximum on the ankle joint angle curve preceded the maximum on the shin inclination curve by some seconds. The records observed during forward and backward platform tilts were qualitatively similar.

3. Changes of the ankle angle during flexion and extension of the hip joint with simultaneous stabilization of the angle of shin inclination

The influence of foot deformation on the change of muscle length and on the angle in the ankle joint was also unequivocally demonstrated by the following experiment. The subject performed slow flexions and extensions in the hip joint on the fixed platform simultaneously trying to maintain the angle of shin inclination at a constant level using visual feedback *via* the oscilloscope (Fig. 4). It could be observed that the muscle length (and hence the angle in the ankle joint) was subjected to a considerable change. In the meantime, the angle of shin inclination remained constant. This experiment permitted to evaluate the foot compliance as a ratio of maximal change of the ankle angle to a shift of the sagittal stabilogram. In the 12 subjects, the maximal value of compliance was about 0.1 deg/Nm and the averaged value was 0.04 ± 0.03 deg/Nm.

4. The vertical displacement of the heel during body tilts

The presence of significant foot deformation was confirmed by a direct independent measurement of the vertical displacement of the clamp fixed on the heel or of the point of fixation of the thread to the calcaneus tuberosity. The subject was asked to incline his body slowly forward or backwards (by 1–2 deg). If there were no foot deformation, we never observed vertical displacements of the heel. But, in all subjects, the change of height of this point over the support surface was 0.5 ± 0.3 mm (the range being 0.1–1 mm) for each degree of body inclination. Taking into account that the distance between the points of maximal foot pressure is about 15–20 cm (Arcan and Brull 1976) and, using the model in Fig. 2B, we could conclude that the magnitude of these small displacements approximately just corresponded to the observed foot compliance and divergence of the two "ankle angles".

5. Differences in foot compliance between subjects

The study revealed great differences in foot compliance among our subjects. However, data have not permitted us to establish a clear correlation between the compliance and the characteristics of the subjects such as sex, age, body mass or physical fitness. A much greater number of subjects would probably be needed to answer the question about the cause of the large interindividual variability. This problem was not in the scope of the present study in which we only tried to test the hypothesis about the marked influences of foot deformation on the ankle angle during standing and to obtain the rough estimates of foot compliance.

6. The relation of foot compliance and parameters of postural regulation

Some correlation between foot compliance and the extent of body deviation from the vertical axis during slow one-degree platform tilt was observed. As was mentioned above, the body sway in different subjects was in the range of 0.5–2 deg. The maximal body deviations exceeding one degree took place only in three subjects. All these three subjects with less accurate body stabilization during slow platform turns belonged to the group with increased foot compliance. This work was performed as a part of a more extensive study of orthograde posture maintenance during slow turns of the support surface. In particular, we also measured the gain in body sway during slow sinusoidal platform tilts. In seven of our subjects with low foot compliance these gains fell in the range from 0.5 to 0.9 (0.7 ± 0.2), the others ranged from 0.7 to 1.9 (1.3 ± 0.4).

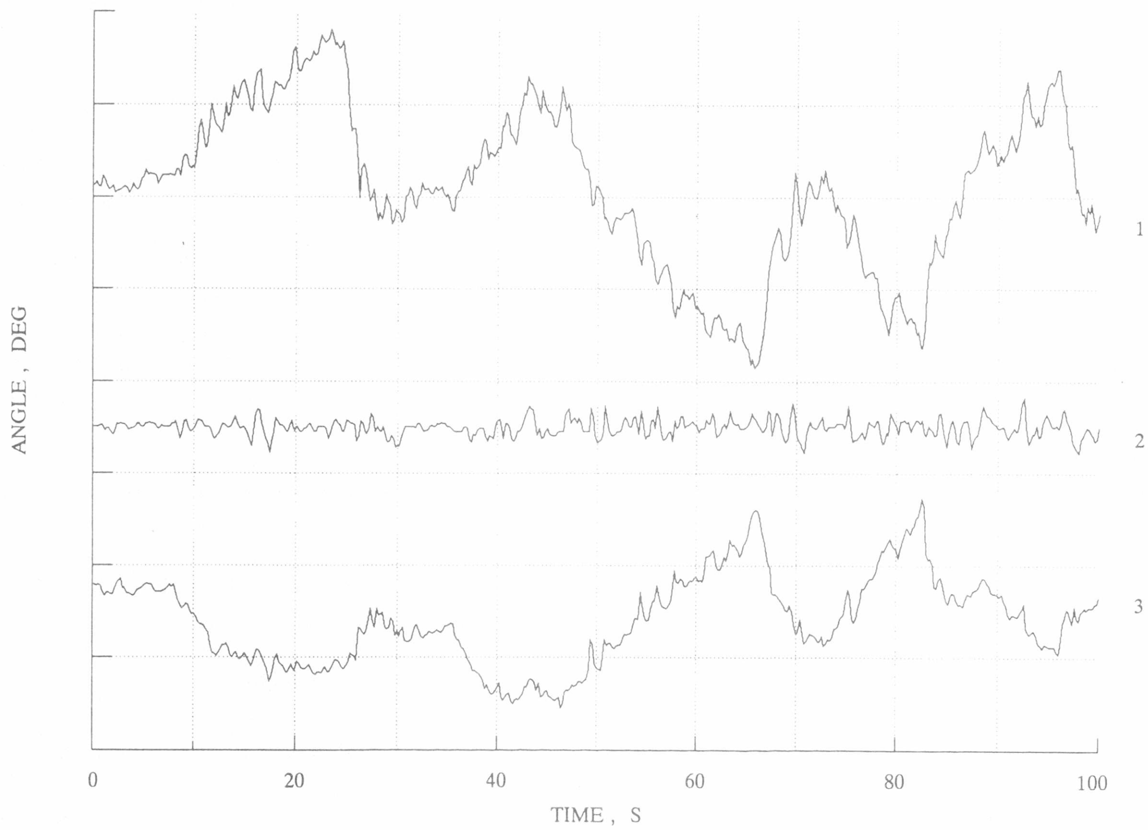

Fig. 4
The slow voluntary flexion and extension in hip joint on immobile platform. The subject was instructed to maintain the constant angle of shin inclination relative to platform using visual feedback via oscilloscope. 1 – stabilogram, 2 – the angle of shin inclination, 3 – the ankle angle calculated on the basis of the changes of projective length of the soleus muscle. One scale division corresponds to 10 Nm for curve 1 and to 1 deg for curves 2 and 3.

Discussion

The compliance of the foot in many subjects during the maintenance of orthograde posture turned out to be sufficiently large. This compliance is probably localized in the soft tissues of the sole and, to a lesser degree, in the foot arch. Thus, if the current changes of muscle length are evaluated using the signal of shin inclination relative to the platform, then in a large group of subjects the measured values of muscle length changes or ankle angle will significantly differ from the real ones, because the foot compliance is being disregarded. Not only the extent of changes but even the general form of the curves can differ from the real ones during standing on a moving platform (Fig. 3). This effect can be easily explained using the model presented in Fig. 2b. It follows from this model that the angle of shin inclination β equals the sum of the angle in the ankle joint γ and the angle of inclination of the "inflexible" part of the foot ξ:

$$\beta = \gamma + \xi$$

It can be assumed that the soft tissues of the foot have definite "sagittal" stiffness. Therefore, ξ would be proportional to the change of torque forces of the support reaction, i.e. to the body sway:

$$\xi = k\,\theta,$$

where k characterizes the foot compliance. So we have:

$$\beta = \gamma + k\,\theta \qquad (2)$$

Finally we obtain using formula (1):

$$\beta = \gamma + k\alpha + k\beta$$

or

$$\gamma = (1-k)\,\beta - k\alpha$$

Thus, the real changes of the angle in the ankle joint depend not only on the shin inclination relative to the platform, but also on the body inclination relative to the vertical axis. During standing on a fixed support ($\alpha = 0$), γ and β are proportional to each other. If α changes during standing, then the degree of divergence of γ and β curves would depend on foot compliance k. Equation (2) gives a good approximation of the difference between curves 3 and 4, as can be seen from the similarity of curves 3 and 3' in Fig. 3. The k factor for this subject was equal to 0.5. It was estimated in the experiment with voluntary flexions and extensions in the ankle joint.

We have so far assumed that the foot behaved as an elastic body. However, it could not be excluded that the deformation of the foot is due not only to the elastic component but also to the plasticity.

The correlation between the foot compliance and the extent of body deviation from the vertical axis during slow a one degree platform tilt seems to be interesting (see section 6 of the Results). It cannot be excluded that mechanical properties of the foot influence the functioning of muscle and joint receptors, and this, in turn, could modify the strategy of postural control during the maintenance of vertical posture. Nevertheless, this question needs further investigation.

Acknowledgements

This work was financially supported by the Russian Foundation of Basic Research, Grants No. 93-04-20520 and No. 93-04-21548.

References

ARCAN M., BRULL M.A.: A fundamental characteristic of the human body and foot, the foot-ground pressure pattern. *J. Biomechanics* **9**: 453–457, 1976.

BURKE D., DICKSON H.G., SKUSE N.F.: Task-dependent changes in the responses to low-threshold cutaneous afferent volleys in the human lower limb. *J. Physiol. Lond.* **432**: 445–458, 1991.

DIETZ V., TRIPPEL M., IBRAHIM I.K., BERGER W.: Human stance on a sinusoidally translating platform: balance control by feedforward and feedback mechanisms. *Exp. Brain Res.* **93**: 352–362, 1993.

FOX J.E., PONSFORD S.: Role of non-muscle afferents in eliciting long latency reflexes in the normal human foot. *J. Physiol. Lond.* **459**: 501P, 1993.

GURFINKEL E.V.: Physical foundation of stabilography. *Agressologie* **14**: 9–11, 1974.

GURFINKEL V.S., LIPSHITS M.I., POPOV K.E.: Is the stretch reflex the main mechanism in the system of the control of vertical posture of man? (in Russian). *Biofizika* **19**: 744–748, 1974.

LIPSHITS M.I.: The influence of interaction between feet and support on tonic activity of leg muscles during standing (In Russian). *Fiziologia cheloveka* **19**: 86–94, 1993.

LISIN V.V., FRANKSTEIN S.I., RECHTMAN M.B.: The influence of locomotion on flexor reflex of the hind limb in cat and man. *Exp. Neurol.* **38**: 180–183, 1973.

NASHNER L.M., McCOLLUM G.: The organization of human postural movements: A formal basis and experimental synthesis. *Behav. Brain Sci.* **8**: 135–172, 1985.

POPOV K.E., GURFINKEL V.S., LIPSHITS M.I.: The influence of interaction between feet and support on reflex responses of ankle joint muscles evoked by vibration (in Russian). *Fiziologia cheloveka* **7**: 716–723, 1981.

POPOV K.E., GURFINKEL V.S., LIPSHITS M.I.: The thresholds of kinesthetic sensibility in orthograde posture (in Russian). *Fiziologia cheloveka* **8**: 981–988, 1982.

PROCHAZKA A., SONTAG K.H., WAND P.: Motor reactions to perturbation of gait: proprioceptive and somesthetic involvement. *Neurosci. Lett.* **7**: 35, 1978.

PROSKE U., MORGAN D.L.: Tendon stiffness: methods of measurement and significance for the control of movement. A review. *J. Biomechanics* **20**: 75–82, 1987.

RACK P.M.H., ROSS H.F., THILMANN A.F., WALTERS D.K.W.: Reflex responses at the human ankle: the importance of tendon compliance. *J. Physiol. Lond.* **344**: 503–524, 1983.

Reprint requests:

Dr. V.S. Gurfinkel, Institute of Information Transmission Problems, Russian Academy of Sciences, Ermolova street 19, 101447 Moscow, Russia.