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Human equilibrium on unstable support: the importance of feet-support interaction

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Abstract

Healthy humans maintained equilibrium on rocking supports (seesaw) of different curvatures and heights. We recorded platform tilt, horizontal displacements of the upper body, ankle joint angle and activity of ankle joint muscles. Subjects maintained balance by making seesaw rotations placing the support under the body's centre-of-gravity. Forward displacement was balanced by compensatory plantariflexion: thus the relation between muscle activity and ankle joint angle differed from that on a rigid floor. Mechanical analysis of stability showed that standing on low seesaws requires ankle torque increase during forward body shift (as on a rigid floor) and torque decrease on high seesaws (when the seesaw height exceeded its radius). In the latter case, balancing was impossible with eyes closed. The results suggest that directionally specific torque changes in response to centre-of-gravity shifts provide important information for maintenance of orthograde posture. © 1997 Elsevier Science Ireland Ltd.

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It is well known that the position of the centre-of-gravity (CG) as well as the geometrical configuration of body segments is accurately controlled relative to the feet and to the direction of gravity [7,12,13]. There are different strategies of equilibrium maintenance during standing on a rigid floor, on a narrow or soft support surface, on a movable support, during locomotion, skating, etc. [1,3–6,9–11,13]. On a solid floor, the body's CG displacement takes place relative to immovable feet. In this case the body can be considered in a first approximation as a single segment with mobility only in the ankle joint. During small perturbations of the support surface the postural response also takes place mainly in the ankle joint. Therefore, we can consider this type of postural control as the ankle strategy.

The aim of this work was to investigate postural mechanisms during standing on the seesaw, in the condition when the feet are not fixed and the usual ankle postural strategy cannot be applied. Earlier the seesaw was used as a way to complicate equilibrium maintenance and to study local oscillations of body parts [1,2]. On the other hand, standing on the unstable support calls upon higher levels of the control system and requires an essential change in mode of utilisation of incoming proprioceptive information. In a previous study [9] we showed that there are different levels of posture control: one is the level of operative control assigned to compensate deviations from a reference position, while another one elaborates this reference. The current study was performed as an attempt to find some general features of the referent vertical and ankle postural strategy both on movable and immovable supports in a normal gravity condition.

Eight healthy volunteers aged from 20 to 45 years participated in this study. The subject stood on a movable support (seesaw) capable of producing translational-rotational movement (rolling) in the sagittal direction. The lower part of the seesaw was curved in the form of a circular sector. We used platforms of different radii of the lower part (0.1, 0.25, 0.45 and 0.6 m) and different heights (from 0.06 to 0.7 m). The platform height (h; Fig. 1A) was increased by add-

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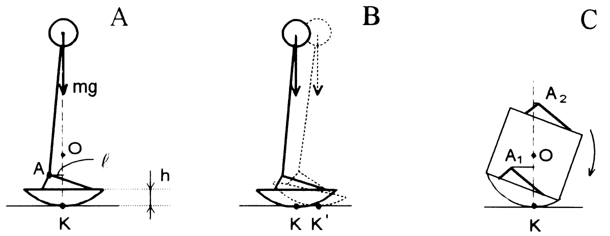

Fig. 1. Peculiarities of the maintenance of body equilibrium on the seesaw. (A) The requirement of equilibrium: the projection of body's CG should coincide with the point of contact of the seesaw with the floor. (B) Change of equilibrium during the change of platform inclination. (C) The direction of ankle joint shift relative to the point 'K' during forward platform rotation: this corresponds to an increase of the gravity force moment arm in case A1 and a decrease in case A2. O, The centre of the circle of the seesaw support; h, seesaw height; *l*, the moment arm of gravity force relative to the ankle joint axis; K,K′, points of contact of the platform with the floor; A1 and A2, axes of the ankle joint on the low and high seesaw, respectively.

ing a wood box or rigid foam plastic of different thickness. The total mass of the platform equalled 3–10 kg. The subject stood with eyes open (except the experiment studying the influence of vision), the centre of the feet coincided with the centre of the seesaw. We recorded the angle of ankle joint, the angle of platform rotation, horizontal displacements of the upper body (breast) and electromyography (EMG) activity of ankle joint muscles (see [8]).

The seesaw possessed an essential property that allowed the subject to maintain equilibrium, i.e. the possibility of translational motion, platform rotation automatically caused a horizontal displacement. In the case studied, balance was maintained by means of horizontal displacements of the support under the feet in the direction of the body's CG shift. The equilibrium was possible at any platform tilt and ankle joint angle, the only necessary condition being the coincidence (within the precision of small oscillations) of the projection of CG and the contact point between the platform and the floor (Fig. 1B).

This conclusion was proved experimentally by small horizontal displacements of breast point relative to the movable support. Actually Fig. 2B shows that the horizontal oscillations of the breast point (curve 5) in a room system of co-ordinates were larger, then in the platform system of co-ordinates (curve 6). On average, during standing on the platform of 0.25 m radius and of 0.23 m height, the horizontal oscillations of the breast point (estimated as a root-mean-square deviation from the mean value) came to 5.8 ± 2.1 mm (mean ± SD) in the room system of co-ordinates but were only 2.9 ± 0.5 mm (two times less) in the platform system of co-ordinates. During standing on the rigid floor they were 3.7 ± 0.9 mm.

Horizontal support displacements in the direction of the body's CG shift were the result of active movements in the ankle joint. The change in the ankle angle was about equal

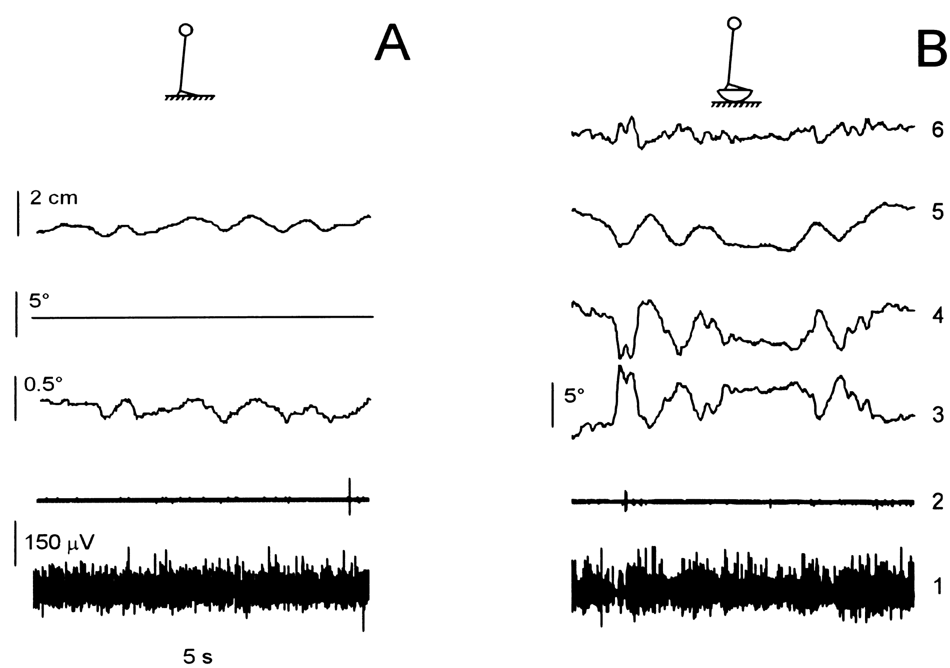

Fig. 2. Balance maintenance on steady (A) and unsteady (B) support. 1, EMG-activity of m.soleus; 2, EMG-activity of m.tibialis anterior; 3, oscillations in the ankle joint; 4, oscillations of the platform; 5, horizontal displacement of the breast point in the room co-ordinate system; 6, horizontal displacement of the breast point in the co-ordinate system of the movable support, obtained from curve 5 after subtracting curve 4 with a coefficient of 0.44 (since the inclination of the platform by 1° is achieved with horizontal displacement of the point of contact between the platform and floor by 0.44 cm). Attention should be paid to the 10-fold difference in the scaling of ankle angle changes on the unsteady and steady support. Positive angular changes correspond to forward body inclination.

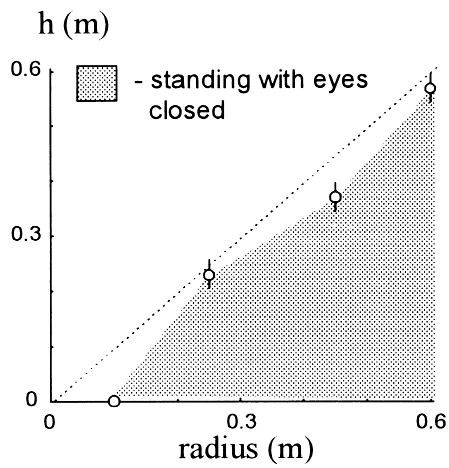

Fig. 3. The influence of seesaw parameters on the possibility of standing with eyes closed. Abscissa, the radius of the seesaw; ordinate, the height of the seesaw. Circles represent mean values of the crucial seesaw height. Subjects could not stand with eyes closed if the height exceeded this value. Error bars, ±1 SD.

to (but in opposite phase to) the change in the inclination angle of the platform and well correlated with horizontal trunk displacements in the forward-backward direction (Fig. 2).

The main mobility took place mostly in the ankle joint. Indeed, if the motion in other joints is small then the angle of body inclination θ equals the sum of the angle of platform rotation α and the angle of shin inclination β:

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

We analysed it in more detail on a platform of 0.25 m radius and of 0.23 m height. Compared to standing on a rigid floor, on the seesaw oscillations of the ankle joint angle were 3–10 times greater (and more than 10-fold in the case shown in Fig. 2). On average, oscillations (root mean square deviation) in the ankle joint equalled $0.18 \pm 0.06°$ in standing on the steady support, and $0.93 \pm 0.37°$ for standing on the unsteady platform. Satisfactory approximation of the angle of trunk inclination (θ) could indeed be obtained by adding the current values of the angle of the platform inclination and the ankle angle in accordance with eqn (1). Such an approximation provided an accuracy of about 1°, while oscillations in the ankle joint reached 5–10°. Thus, one can consider this type of postural control as the ankle strategy.

EMG-activity of shin muscles during standing on the rigid floor and on the seesaw resembled each other. There was a moderate level of soleus activity, tibialis anterior was almost inactive in most cases. However, during standing on ‘more unstable’ seesaws (high seesaws or seesaws of small radius) the amplitude of the movements in the ankle joint was larger and we observed a marked modulation of EMG-activity of the soleus muscle. The forward body displacement was accompanied by a compensatory plantariflexion in the ankle joint that displaced the support under the body’s CG. As a result, EMG activity of soleus increased during muscle shortening, but not lengthening (Fig. 2).

Thus, on the rigid floor the triceps surae muscles generally work in an eccentric mode of contraction and on the seesaw, in a concentric one. Therefore, despite a formal use of the ‘ankle postural strategy’, the sensory organisation and real mechanisms of stabilisation of CG differed from those on a rigid floor. On the movable support the task of the equilibrium maintenance cannot be solved by a tracing of a pre-set value of the ankle joint angle or of the ankle torque. Balance was maintained by means of horizontal displacements of the support in parallel with the body’s CG shift.

It is worth noting that humans could stand on the movable platform without large efforts or any preliminary practice. Yet, subjectively it was easier to stand on low seesaws of large radius. This might characterize the construction of the vertical reference and the sense of stability on the movable support. We studied the possibility of maintaining equilibrium with eyes closed. As a positive result, we accepted trials in which subjects did not loose equilibrium during 20–30 s. We found that for all subjects the balance with eyes closed was impossible when the height of the seesaw was more than its radius, an experimenter in such cases should prevent them from falling (Fig. 3).

In our view, this finding reflects fundamental properties of human postural control in a gravitational environment. Peculiarities of feet-support interaction can give us the key for understanding such an intriguing dependence. The horizontal support movement depends on its angular displacement α and is equal to $r \times \alpha$, where r is the radius of the platform. Thus, it is independent of the platform height. From this point of view it is easier to perform horizontal support displacements on the seesaw of the larger radius since the same active change in the ankle joint angle causes the larger horizontal support displacement. Still, our results demonstrate that the height was also of importance.

This finding can be well explained by a particular change of the ankle torque during platform inclination. This is clearly illustrated by Fig. 1A,C. According to the requirement of equilibrium (Fig. 1A), horizontal displacement of the platform should be accompanied by an appropriate change in the moment arm of a gravitational force and, thus by a change in the ankle torque. This change is related to the platform height, being positive or negative depending on whether it is less than the radius or not (Fig. 1C). Indeed, equilibrium requires that the forward body shift always be balanced by a plantar flexion in the ankle joint. However, stability requires that the ankle torque increases for low seesaws (as on the rigid floor) and decreases for higher seesaws (‘unnatural change’) (Fig. 1C). The results showed that equilibrium with eyes closed was possible only in the first case.

As was noted above the investigations of the standing on the movable support in the past have been extensive, but somewhat one-sided [1–3,5]. Our study shows that standing on the seesaw is not just the standing in more difficult conditions (a kind of a test with additional 'load'); the careful analysis of biomechanics could provide important data revealing some general features of postural control.

Two points should be stressed in relation to results obtained. Firstly, on the rigid floor forward CG shift is accompanied by correlated changes in ankle joint and distribution of feet pressure; this posture disturbance is compensated by activation of triceps surae muscles returning CG projection to a accustomed 'spot' within support contour. On the seesaw the equilibrium is also maintained by changes in ankle joint angle, and formally one could speak about 'ankle joint strategy' [10]. However real regulation pattern is quite different: human does not move his CG, he rather shifts the point of contact of the seesaw with a floor under his CG. The relations between sensory inputs and motor actions in this case differ from those during standing on the floor. So 'ankle strategy' in fact could be not a strategy, but just one of the 'tactics' providing a solution of really 'strategic' task, i.e. stabilisation of a spatial position of the trunk.

The second point is connected with sensory organisation of standing. It is generally accepted that visual, vestibular and proprioceptive signals contribute to maintenance of orthograde posture [4,10,12]. Our data reported elsewhere [9] suggest that proprioceptive inputs play an especially important role in the elaboration of postural reference. The present study confirms this conclusion and indicates that the centre of foot pressure, that is the ankle torque is one of the main control parameters of human upright posture. On the rocking seesaw continuously changing its orientation, it is difficult to use propioceptive information about relative positions of successive links of kinematic chain for the construction of internal representation of body position relative to vertical. Nevertheless, a directionally specific torque changes in response to CG shifts provide a sufficient reference in the gravitational environment, especially in the absence of visual cues. The control occurs in relation to this kinaesthetic reference elaborated as a construct by analyzing interrelations of torque changes and body displacements.

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