Exp Brain Res (1995) 106:327–338

RESEARCH ARTICLE

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Head and trunk movements in the frontal plane during complex dynamic equilibrium tasks in humans

Received: 16 June 1994 / Accepted: 28 April 1995

Abstract Eight normal human subjects were asked to maintain monopodal equilibrium on a narrow beam (task 1) or bipodal equilibrium on an unstable rocking platform (task 2) for 5 s. Each task was performed under four experimental conditions: (1) in light, (2) in darkness, (3) in light while subject had to hold a full cup of water, and (4) as in 3, but with additional instructions to fix the gaze on the cup. The movements of the trunk and head in the frontal plane were recorded by means of a 50-Hz TV image analyzer that computed the coordinates of small reflective markers glued on the skin of the subjects. On the beam the trunk was inclined on the side of the supporting foot (13±9°), on the rocking platform the mean trunk orientation during the tests was nearly vertical (2±7°). Nevertheless, in both tasks the mean head position was the same and close to vertical: 1.5±4° on the rocking platform and 1.5±5° on the beam. For both tasks and all experimental conditions the head remained stabilized relative to vertical, despite large translations in the frontal plane. Standard deviations of head orientation from its mean value were 2.8±2° for task 1 and 2±1.5° for task 2. The changes of trunk orientation were significantly higher: 6.2±4.8° and 4.5±4°, respectively. The differences in angular stability of head and trunk, measured through the standard deviations of angular displacements, were especially pronounced in trials with large trunk movements. It was concluded that head angular stabilization, providing the central nervous system with necessary visual and vestibular references, is essential for effective dynamic postural control in the frontal plane during complex equilibrium tasks.

Key words Lateral stability · Head orientation · Postural references · Human

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Introduction

Lower limb strategies involved in the maintenance of equilibrium have been extensively and clearly described during unexpected movements of the support surface. Using this "bottom-up approach," which explains postural control from lower limb to upper limb, Horak and Nashner (1986), for instance, have identified distinct postural reactions at the hip and the ankle level in response to support surface translation. Further, Shupert et al. (1988) demonstrated that the head is stabilized in space in response to support surface translation. It must be stressed that the majority of these studies have been restricted to the examination of the adaptation of motor output to unexpected perturbation with the kinesthetic information from lower limbs as the main source of feedback. However, it has been speculated that the major regulation during the control of complex equilibrium tasks is through anticipatory mechanisms (Droulez et al. 1985).

Thus, instead of the classical "unexpected perturbation approach," in which postural control has been restricted to the question of reactive response to perturbations of stance, we are interested here in studying the active control of posture in complex equilibrium tasks. We selected two tasks that require fine balance (monopodal equilibrium on a beam and bipodal equilibrium on a rocking platform) and in which the equilibrium is actively planned on the basis of a predictive mode of sensory input selection (Droulez and Berthoz 1986; Gurfinkel and Levik 1991).

We have demonstrated previously that during locomotion (Berthoz and Pozzo 1988, Pozzo et al. 1990) angular displacements of the head in the sagittal plane are minimized within a few degrees, and that during other goal-directed tasks (jumping, acrobatic leaps) head rotation is stabilized in a intermittent fashion. We have suggested that head stabilization optimizes the sensitivity to visual and vestibular signals, also confirmed by Keshner et al. (1992) and Grossman et al. (1988), who reported an efficient vestibulo-ocular reflex (VOR) during locomotion. Consequently we proposed that the head position could be used for constructing a stable frame of reference (inertial guidance platform) from which dynamic equilibrium is organized. Recently, in the framework of this "top-down approach," head stabilization has also been demonstrated in children during locomotion on a beam (Assaiante and Amblard 1990). Further, Mouchnino et al. (1990), studying the coordination between posture and movement, have shown that the head is stabilized during a voluntary abduction of the leg.

The purpose of this study is to extend our previous investigations (Pozzo et al. 1989, 1990) to angular displacements of the head in the frontal plane and to test the hypothesis of head stabilization during two tasks which require especially fine lateral control. Postural readjustments in the frontal plane have been studied mainly during roll motion of a large visual scene in front of the observer (Dichgans et al. 1972; Mauritz et al. 1977; Clément et al. 1985). In this plane, joint mobility is lower than in the anterior-posterior direction; therefore, Mauritz et al. (1977) suggested that lateral body sway should be described by a multilink model with several joints controlling equilibrium rather than an inverted pendulum. In addition, head tilting in the frontal plane cannot be compensated efficiently by vision because of the poor performance of the VOR in torsion (Collewijn et al. 1985). In the current study, our objective was to determine the specific roles of the head and trunk during dynamic postural control in the frontal plane. Our hypothesis was that head angular displacement will be minimized relative to the trunk, and hence provide a stable visual and vestibular frame of reference.

Other studies on posture and movement coordination demonstrated that subjects can stabilize in priority other body segments, the arm (Hugon et al.1982) or the hand, when the subject holds a cup full of water (Marsden et al. 1981; Droulez 1988). Marsden et al. (1981) show that postural reactions tend to stabilize the hand at the expense of the other limbs. Droulez (1988) suggested that during this task the stabilization of the cup could be achieved by using different geometrical postural configurations (or topologies), where the hand can be stabilized independently of head and trunk movements. Consequently, we wanted to verify whether during tasks involving stabilization of a distant limb the head remains stable in the frontal plane. For this we asked subjects to maintain equilibrium while holding a full cup of water. In addition, in order to verify whether the head linked to a distal body reference improves postural stability, the subjects were asked to anchor their gaze on the cup. A preliminary account of some of the results has been presented previously (Pozzo et al. 1992).

Materials and methods

Subjects and tasks

Eight voluntary subjects (one woman and seven men), ranging in age from 25–40 years, with no previous history of vestibular, orthopedic, or neuromuscular disease were tested during two different tasks. In the first task they were asked to maintain an upright monopodal stance on a narrow cylindrical *beam* (7 cm in diameter) fixed on the floor. In the second task they had to maintain an upright bipodal stance on an unstable *rocking platform* (50 cm long, 30 cm wide) mounted on a cylinder (25 cm in diameter) with the axis parallel to anterior-posterior body axis. The platform is attached at a fixed point on the surface of the cylinder, thus the platform can rock in the frontal plane. Subjects were barefoot.

These two tasks, which require fine equilibrium in the frontal plane, have been chosen because they represent two kinds of postural tasks:

1. On the beam, the difficulty of the task is due to the small and spherical surface of the support; it provides solid support surface for one foot.
2. On the rocking platform, the movement of the support surface is primarly a rotation; however, because this axis of rotation does not pass through the platform, a linear translation also occurs: 1° of rotation corresponds to 3 mm of translation. Consequently, there is no absolute (exocentric) stable tactile frame of reference.

The two tasks were performed in the light (L) and in darkness (D), in a room with the walls located at a distance of 4 m. In the light the experiment was first performed without upper limb constraints and then with the subject holding a cup full of water in his dominant hand. In the latter situation, two visual conditions were tested: (1) the subject was free of specific instructions regarding gaze (C) and (2) he or she was required to anchor his or her gaze on the cup (G). Each experimental condition was tested three times, with a duration of data acquisition of 5 s in each trial and always in the same order (L, D, C, and then G, first on the beam and then on the rocking platform). Each trial was organized as follows:

1. On the beam, the subject initially stood with one foot (freely determined by the subject) on the beam and the other on the ground. Data acquisition began when the subject raised the foot off the ground.
2. On the rocking platform, an experimenter helped the subject to stand on the platform. Data acquisition began when the subject maintained his equilibrium without help.

A tone indicated the beginning and the end of a trial. A training period of 10 min before each recording session was devoted to familiarize the subjects with the two equilibrium tasks under normal visual conditions. A recording session included 24 trials (2 tasks×4 experimental conditions×3 repetitions).

The movements of various parts of the body were measured with a 50-Hz TV image analyzer that computed the coordinates of small reflective markers glued on the skin of the subjects. For a detailed description of the methods for movement analysis using this system, see Pozzo et al. (1990). In the present study, the two cameras were placed in front of the subject in order to record the displacement of six markers fixed on the forehead, the chin, the sternum, the navel (near the medial line of head and trunk), and on the lower limbs on the distal part of the tibialis (Fig. 1A,B). These markers, which define four links, allowed us to compute the orientation angle in the frontal plane of the head, the trunk, and the lower limbs. In this experiment we have not take into account each axis of rotation provided by each verterbra, and the trunk was assimilated to a rigid segment with one axis of rotation approximately located near the navel. Kinematic analysis has verified such a model by demonstrating a deformation of the link connecting the markers located on the sternum and the navel during trunk lateral tilt less than 5%. Under the present conditions, in which the observed field of view was 3 m by 3 m, the accuracy was on the order of 1–1.5 mm for linear displacement and 1.5° for angular position.

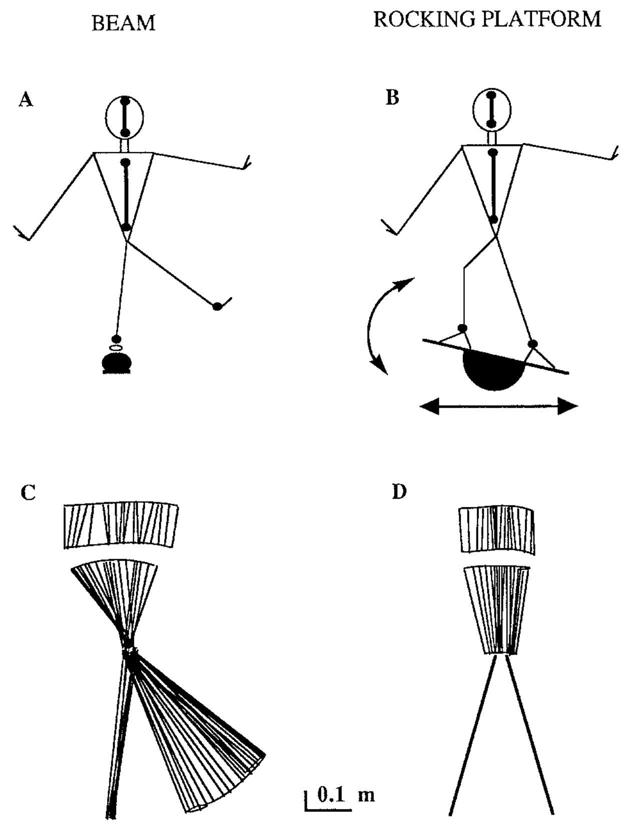

Fig. 1A–D The experimental tasks. The subjects maintained an upright monopodal stance on a narrow cylindrical beam fixed to the floor (**A, C**) and an upright bipodal stance on a unstable platform (**B, D**). On the rocking platform (**B**), *solid arrows* depict the induced rotation and lateral translation movements of the feet. **A, B** The *full circles* indicate the positions of the six markers that were placed on body segments. **C, D** Links between markers were reconstructed by computer for the two respective tasks. On the rocking platform, only links on the head and trunk have been reconstructed

Data analysis

Several kinematic measurements in translation and in rotation have been chosen to describe the subject's postural strategies in the frontal plane. The head and trunk angular positions (θ and α) were determined by calculating the angle between the vertical axis (z) and the line connecting the two markers placed on each one of those two segments (see right hand part of Fig. 2). Zero values for θ and α indicate a vertical alignment for the head and the trunk, respectively. Head and trunk angular velocities (θ' and α') and accelerations (θ'' and α'') were also derived from the markers positions. Positive values indicated an inclination on the side of the foot support with respect to the z-axis, while negative values represented inclination on the opposite side (the bottom markers of each segment represented the axis of rotation). The mean head and trunk angular displacements, velocities, and acceleration were obtained for an entire recording session. The standard deviation (σ) of the angular displacement were used to give an estimate of head and trunk stability in lateral tilt. Because of the equal distribution during one trial of positive and negative velocities and accelerations around zero value, the standard deviations were also used to evaluate the mean value of angular velocity and acceleration of the head (respectively σθ', σθ'') and of the trunk (σα', σα''). In order to evaluate the dispersion of the values we have calculated the coefficient of variation (CV), which corresponds to the ratio of the standard deviation to the mean value.

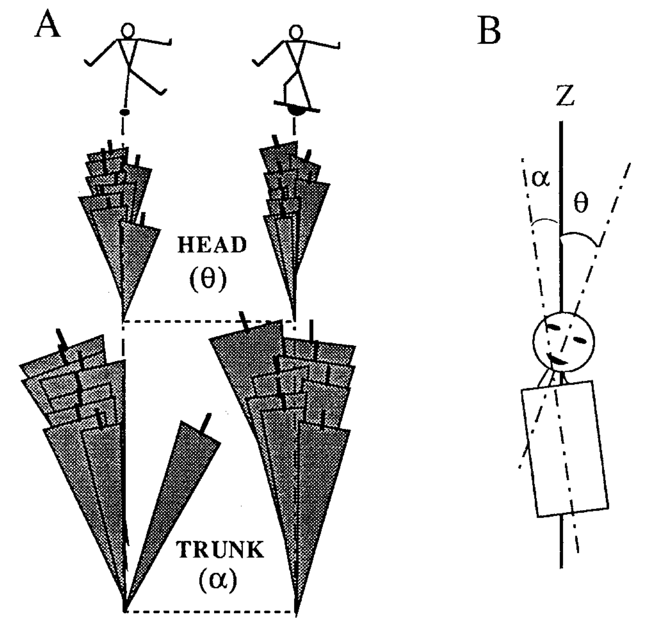

Fig. 2 A Head and trunk angular positions when the subjects stood on the beam (*left*) and on the rocking platform (*right*), averaged for all experimental conditions tested. Each *triangle* summarizes for each subject the mean amplitude (delimited by the corners of the base of each triangle) and the mean orientation (*thick bar* at the top of each triangle) of SD of head and trunk angular displacement with respect to the vertical axis (*vertical dashed line*). **B** The caricature indicates how α and θ were calculated

An analysis of variance (ANOVA) was performed on the parameters described above (linear and angular descriptors of the movement) with the four experimental conditions (L, D, C, G) and the two tasks (beam and rocking platform). For each of those parameters, the effect of each factor alone as well the interaction between them is indicated. Scheffé's F-test was used as a post hoc test. A κ level corresponding to $P<0.01$ has been selected for all statistics.

Results

General characteristics of head and trunk linear and angular stability during two tasks

Group data of head and trunk translation and rotation in the frontal plane are summarized in Tables 1 and 2, and Fig. 4. Standard deviations of the head translation along the lateral axis are significantly greater than the corresponding values for the trunk ($F_{1,346}$=28.2, $P<\kappa$). In contrast, standard deviations of head lateral tilt in the frontal plane are significantly smaller than the corresponding values for the trunk ($F_{1,346}$=76.8, $P<\kappa$).

Under all experimental conditions tested on the two supports, the linear displacement, velocity, and acceleration along the lateral axis of the markers placed on the forehead did not exceed 500 mm, 850 mm/s, and 6000 mm/s^2. For the marker placed on the sternum, maximum values are, respectively, 250 mm, 600 mm/s, and 3000 mm/s^2.

Head and trunk horizontal displacements in translation (see Table 1) are not significantly different on the

Table 1 Summary of group data of the amplitude of head (X_h) and trunk (X_t) displacement, velocity (X'), and acceleration (X'') in translation along the horizontal axis averaged in the eight subjects tested (±standard deviations) during the two equilibrium tasks and the four experimental conditions. Head and trunk linear displacement have been evaluated trough the displacement of the markers placed, respectively, on the forehead and on the sternum

Experimental conditions	Displacement (mm)		Velocity (mm/s)		Acceleration (mm/s²)	
	X_h	X_t	X'_h	X'_t	X''_h	X''_t
Beam						
Light	45±34	26±19	124±86	67±46	721±421	422±254
Darkness	70±36	45±18	168±81	98±40	963±403	602±426
Cup	36±16	23±10	80±44	53±25	560±268	395±234
Cup+gaze	34±16	23±18	83±49	50±31	451±206	366±231
Rocking platform						
Light	36±28	23±16	89±60	50±32	550±387	350±315
Darkness	67±50	48±42	130±118	79±63	760±690	530±382
Cup	30±23	21±17	65±34	42±19	419±223	330±200
Cup+gaze	23±12	17±8	48±26	33±16	414±378	234±188

Table 2 Summary of group data of standard deviations (σ) of velocity and acceleration of head (θ) and trunk (α) angular displacement in the frontal plane averaged in the eight subjects tested (±standard deviations) during the two equilibrium tasks and the four experimental conditions

Experimental conditions	Velocity (deg/s)		Acceleration (deg/s²)	
	$\sigma\theta'$	$\sigma\alpha'$	$\sigma\theta''$	$\sigma\alpha''$
Beam				
Light	11.8±8.5	19±13.5	134±99	135±88
Darkness	15.4±10	27±15	176±190	183±88
Cup	10±2.7	17±10	151±98	124±70
Cup+gaze	9.3±3.7	13±8	109±57	99±56
Rocking platform				
Light	9.3±5.2	15±11.3	128±111	146±98
Darkness	13.3±9.4	22±21.5	172±95	200±135
Cup	7.7±2.9	12±7.2	120±100	130±100
Cup+gaze	7.8±4	8.8±5	141±152	76±45

Table 3 Mean values of maximum head (θ) and trunk (α) angular amplitude, velocity, and acceleration during the two equilibrium tasks averaged in the four experimental conditions

	Amplitude (deg)	Velocity (deg/s)	Acceleration (deg/s²)
Beam			
θ_{max}	11.8±34	33±11	454±175
α_{max}	23.4±36	46±18	412±153
Rocking platform			
θ_{max}	8.5±3	27±13	425±262
α_{max}	17±9	40±23	425±250

rocking platform compared with the beam. In contrast, trunk lateral tilt is significantly greater on the beam than on the rocking platform ($F_{1,92}$=6.3, $P<\kappa$). On the beam, the mean values of σ_θ (head lateral tilt) and σ_α (trunk lateral tilt) averaged over all experimental conditions are, respectively, 2.1±2° and 6.3±4.8°. On the rocking platform these values are equal to 2±1.5° ($\sigma\theta$) and 4.5±4° ($\sigma\alpha$). Mean maximum head and trunk angular displacement, velocity, and acceleration values for the beam and the rocking platform are given in Table 3.

Mean head and trunk angular positions on the beam and the rocking platform

To verify that the subjects did not adopt abnormal head or trunk postures at rest, before each recording session we measured head and trunk angular positions in the frontal plane when the subject stood quietly on the floor. In all eight subjects tested, resting head and trunk orientations proved to be almost vertical, the mean values and SD of θ and α being, respectively, 0.5±2° and 1±2°. Subsequently, the angular positions of head and trunk during equilibrium tasks were calculated relative to the resting positions during standing on the floor. Stick figures illustrating postures adopted by typical subjects and movements of body segments during equilibrium maintenance on the beam and on the rocking platform are shown in the lower part of the Fig. 1.

Figure 2 illustrates the mean head and trunk angular positions during the two equilibrium tasks for each of the eight subjects tested. Each angular sector corresponds to the mean amplitude of head and trunk angular displacements in the frontal plane, averaged over all trials in one subject. There is a significant difference in head and trunk angular position on the beam compared with the rocking platform ($F_{1,346}$=12.6, $P<\kappa$) with a significant second order interaction between head and trunk position and the tasks (beam and rocking platform) ($F_{1,346}$=9.9, $P<\kappa$).

On the beam, the mean head angular position averaged for all experimental conditions is slightly different for each subject, but remains near the vertical axis. The mean value of θ averaged over the eight subjects is 1.5±5° (see Fig. 2). This small deviation of the head on the side of the foot support, which is of the same order during L, D, and C conditions, tends to be greater (not significantly) when the subjects are required to fix their eyes on the cup (G; θ=3±7°). This angular deviation of the head could be the result of the orientation of the gaze in the direction of the cup, which was located downward

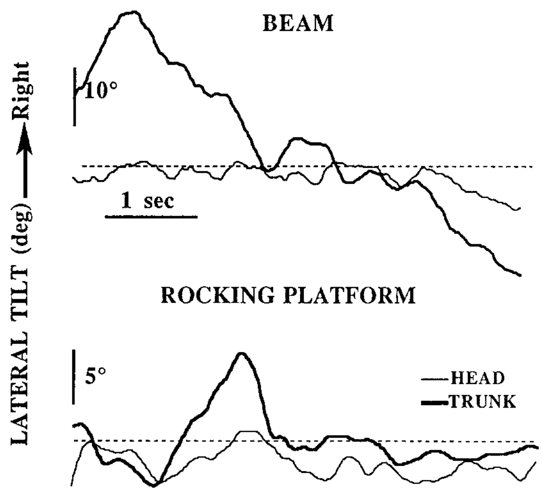

Fig. 3 Head (*thin trace*) and trunk (*thick trace*) angular displacements on the beam (*upper part*) and on the rocking platform (*lower part*) in the frontal plane, plotted as functions of the time for 5 s and during one single representative trial. *Horizontal dashed lines* indicate the earth-vertical. Note the larger angular displacement of the trunk on the beam than on the rocking platform (scales for plots are different)

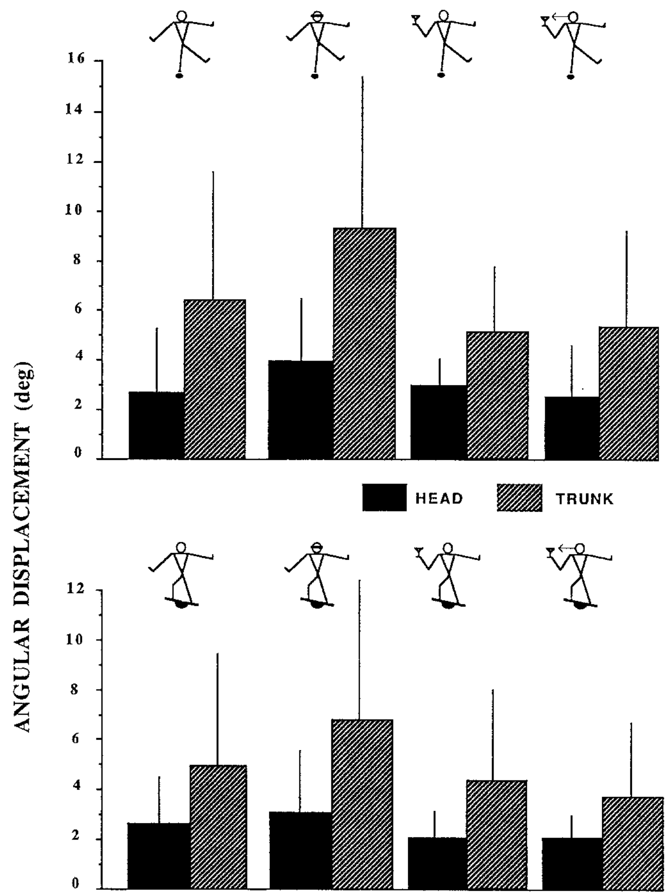

Fig. 4 Amplitude of head and trunk angular displacements in the frontal plane for the two tasks tested and during the four experimental conditions. Each histogram bar shows the mean value of σ_θ and σ_α (+SD), averaged over the eight subjects tested. The stick figures show the experimental conditions on the beam (*top*) and on the rocking platform (*bottom*): in the light, in darkness, with the subject holding a cup full of water, and when the subject anchors their gaze on the cup

at the level of the navel about 50 cm on the right side of the sagittal plane and about 40 cm in front of the frontal plane.

In contrast with head angular position, the mean angular position of the trunk was significantly deviated from its vertical resting position ($P<\kappa$ with Scheffé's *F*-test), the trunk being tilted on the side of the foot support (α=13±9°). Only one subject, among the eight tested, stood on his left foot and consequently tilted the trunk to the left side. Neither darkness nor holding the cup of water (with or without gaze fixation) had a significant effect on mean trunk angular position.

On the rocking platform, both head and trunk mean angular position are equally distributed on each side of the vertical axis. The mean value of θ and α averaged over the four experimental conditions and the eight subjects being, respectively, 1.5±4° and –2±7° (Fig. 2). In contrast with the beam, there is no significant difference between head and trunk values. Differences between beam and rocking platform concerning head and trunk angular positions are illustrated in one typical subject in Fig. 3.

Effects of experimental conditions

There was a significant effect of the four experimental conditions (L, D, C, G) on head and trunk linear displacements ($F_{3,346}$=28, $P<\kappa$) and accelerations ($F_{3,346}$=16, $P<\kappa$) in the frontal plane (see Table 1). This effect can be mainly attributed to the darkness condition, where head and trunk linear displacement increased significantly compared with L, C, and G conditions (*P* values always below 5% with Scheffé's *F*-test) both on the beam and on the rocking platform, and for the head and the trunk).

There was a significant effect of the four experimental conditions (L, D, C, and G) on head and trunk angular displacement ($F_{3,346}$=9.6, $P<\kappa$) (see Fig. 4), velocity ($F_{3,346}$=15.2, $P<\kappa$), and acceleration ($F_{3,346}$=7.3, $P<\kappa$) (see Table 2) without second order (head vs trunk) or third order (beam vs rocking platform) significant interactions.

On the beam, head angular displacements were not significantly different in the four conditions of movement. Trunk angular displacements were significantly different in the four conditions of movement ($F_{3,86}$=5.2, $P<\kappa$). In darkness the amplitude of trunk angular displacement increased significantly (with Scheffé's *F*-test) compared with C ($F_{3,21}$=4.9, $P<0.05$) and G ($F_{3,21}$=4.1, $P<0.05$). For trunk angular acceleration, the values obtained in darkness increased significantly (with Scheffé's *F*-test) compared with C ($F_{3,18}$=3.5, $P<0.05$) and G ($F_{3,18}$=3.4, $P<0.05$). On the rocking platform head and

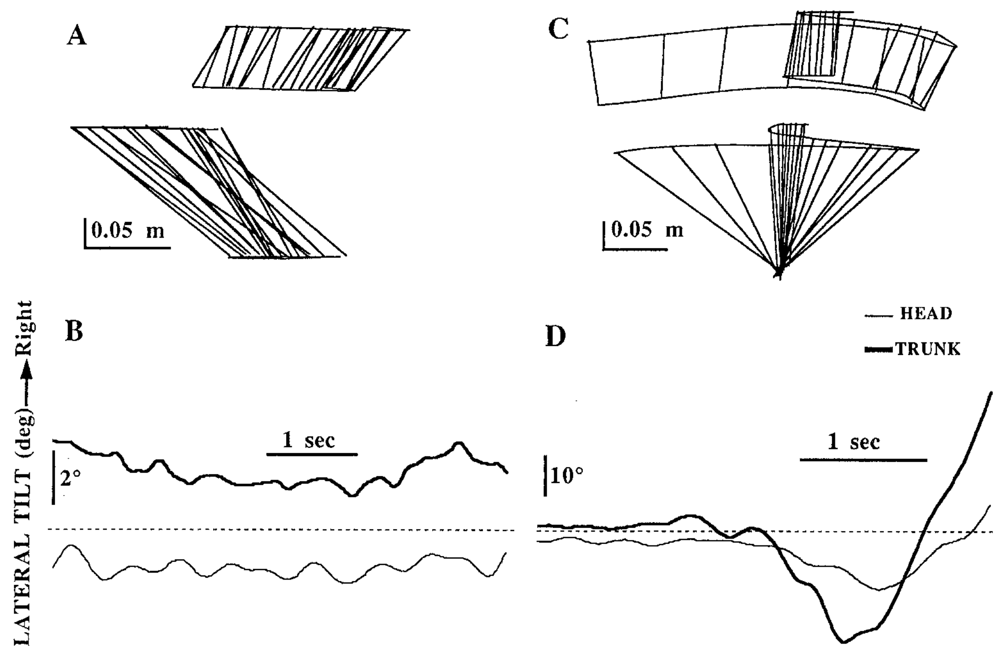

Fig. 5A–D Typical raw data of head and trunk position (**A, C**) and rotation (**B, D**) on the beam in one very stable subject (*left*) and when the subject lost his equilibrium (*right*) and fell down to the right before the end of the trial. Note the different scales on the *lower left* (**B**) compared with the *lower right* of the diagram (**D**)

trunk angular values were not significantly different in the four conditions of movement.

Despite the decrease in stability in darkness, head and trunk angular displacements remain in a small range of values ($\sigma\theta$=4±2.5° and $\sigma\alpha$=9.5±6°). However, in the absence of visual information, the subjects report more difficulty in the maintenance of equilibrium, especially on the beam. During this task, five subjects among the eight tested fell twice before the end of the 5-s recording session. On the rocking platform, the same five subjects each fell once. During these episodes, the subjects were asked to try again until they maintained their equilibrium on the beam and on the rocking platform for 5 s. In Fig. 4, histogram bars have been calculated by considering only the successful trials. This could explain the rather good performance of the subjects, considering the difficulty of the task. Thus, on the beam in darkness the coefficients of variation of $\sigma\theta$ and $\sigma\alpha$ (respectively, CV=0.60 and CV=0.64) decrease compared to the light condition (respectively, CV=0.90 and CV=0.76), indicating a smaller dispersion of the values in darkness.

An example of a trial in darkness including the sequence of events leading to a loss of balance is shown in Fig. 5C,D. At the beginning of the trial the subject maintained very precise stabilization of both head and trunk. Then the trunk began to incline, while the head remained well stabilized. However, without vision the subject did not succeed in maintaining a vertical head orientation for long: the trunk rotation abruptly changed direction and the head began quick lateral tilt in the direction of trunk inclination. Finally the subject lost his equilibrium and fell before the end of the trial.

When the subject holds the cup filled with water, both with and without gaze instructions (G and C), the amplitudes of head and trunk linear and angular displacements are not significantly different from L and D conditions on the beam and on the rocking platform. Gaze fixation on the cup does not significantly affect head and trunk angular displacement. Nevertheless, on the beam the dispersion of the values of $\sigma\theta$ (CV=0.80) and $\sigma\alpha$ (CV=0.76) in G are larger than in C (respectively, CV=0.40 and CV=0.53), indicating more irregularity in head and trunk angular movements than in C.

When the subjects held the cup full of water, only two of the eight subjects reported that they felt more stable when they fixed their eyes on the cup than in the condition without gaze instructions. The other six felt less or equally stable. It should be noted that the subjects generally reported that under normal conditions (in the light and without the cup) their gaze was directed at a point on the ground about 2 or 3 m ahead of their feet.

Differences in head and trunk postural strategies

In order to clearly show the difference between head and trunk rotations, we have plotted in Fig. 6 the standard deviations of head angular displacements ($\sigma\theta$) as a function of trunk angular displacements ($\sigma\alpha$) on the beam (left) and on the rocking platform (right). The values obtained for all experimental conditions and for all subjects tested are plotted together.

Several observations which hold for the beam and the rocking platform can be made from Fig. 6:

1. The data points are mainly distributed above the diagonal line, confirming graphically that the SD of head lateral tilt is less than that of trunk lateral tilt. Nevertheless, in the low-range values of head lateral tilt ($\sigma\theta$<2.5°) there are several points located under the diagonal, especially on the beam, where some data points (about 25%) are distributed along an axis close to the horizontal axis;

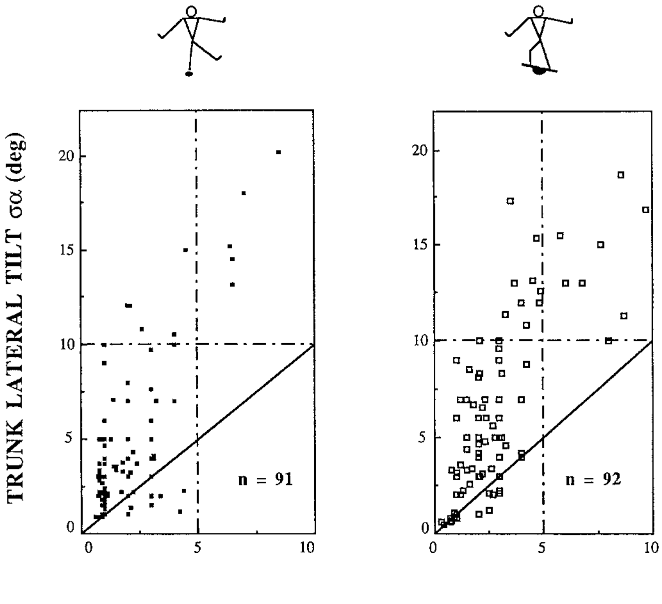

Fig. 6 Head rotation versus trunk rotation in the frontal plane. Standard deviation of head rotation (σθ) is plotted as function of the standard deviation of the rotation of the trunk (σα) in the frontal plane on the beam (*left*) and on the rocking platform (*right*) for the eight subjects in all experimental conditions. Note that the data points are mainly distributed above the diagonal, indicating that head rotation is less than trunk rotation (*n* number of samples)

these points indicate a better angular stabilization of the trunk than of the head for small oscillations.

2. The points are mainly situated on the left side of a vertical dashed line, indicating that the SD of the head rotation (σθ) generally do not exceed 5° for all experimental conditions. For the trunk, angular displacements (σα) can exceed 15°. We can also note some isolated points located in the upper right of Fig. 6, indicating that for larger trunk angular displacements (σα>10°; points located above the horizontal dashed line) the SD of head angular displacements increase, sometime exceeding 5° but never surpassing 10°.

Together, these two observations suggest that on the beam during small postural imbalances the trunk is sometime better stabilized than the head; conversely, for larger postural disturbances the head is better stabilized than the trunk. In Fig. 5A,B is shown the postural strategy adopted by a subject with especially high stability. It can be seen from stick figures and angle-time plots that in this subject both head and trunk lateral tilts are very small.

Correlations between head and trunk movements on the beam

Cyclograms of angular displacements of head and trunk on the beam

To study the nature of the dynamic relations between the angular displacements of the head and trunk, we have plotted the evolution of the angular position of the head in the frontal plane (abscissa) and of trunk lateral tilt in the same plane (ordinate). Figure 7 shows examples of such plots for a typical subject. A mean trace oriented along the vertical indicates a perfect head stabilization, and a slope oriented along the horizontal indicates a perfect trunk stabilization. Diagonal traces indicate synchrony between head and trunk movements. A positive slope reflects movements in the same direction, whereas a negative slopes indicates movements in the opposite direction.

Under light conditions (Fig. 7A), the relations between θ and α are almost linear. The linear relations between head and trunk angular displacement are illustrated by trace orientation along a diagonal, which suggests a positive correlation between the angular displacements of head and trunk. Nevertheless, the higher density of the trace in the center of the plot indicates that the lateral tilts of the head and trunk are mostly of small amplitude.

In darkness (Fig. 7B), the mean trace is oriented along a straight vertical line. However, in the lower part of the plot one can observe a loop oriented perpendicular to the main part of the trace. In other words, this result indicates that (a) during trunk displacements of large amplitude (30°<α<10°) the head remains stabilized along the vertical, and (b) the quick head movements of great amplitude (here almost 35°) are possible during equilibrium maintenance without involving the trunk.

When a subject holds a cup filled with water without conditions imposed on gaze direction or with instructions for gaze fixation on the cup (Fig. 7C,D), the trace is more complex, indicating a less regular relation between θ and α. However, under conditions of gaze fixation on the cup it is possible to distinguish two parallel lines with positive slope, along which the trace is mostly oriented. This pattern resembles those obtained under light conditions.

Correlations between angular accelerations of head and trunk

To quantify the observations described above, we have calculated correlation functions between angular acceleration of the head and those of the trunk. The method of calculation has been described elsewhere (Pozzo et al. 1990). The correlation function was obtained from two time series (the angular acceleration of the head and that of the trunk as functions of time) for temporal shifts from –80 to +80 ms. A correlation coefficient smaller than 0.5 corresponds to uncoupling of head and trunk movement in the frontal plane. A positive value of the correlation coefficient indicates that lateral tilt of head and trunk have mostly the same direction. The angular accelerations were chosen as variables because they are proportional to the resulting muscular forces and because head acceleration is one of the physical parameters that the vestibular system itself encodes.

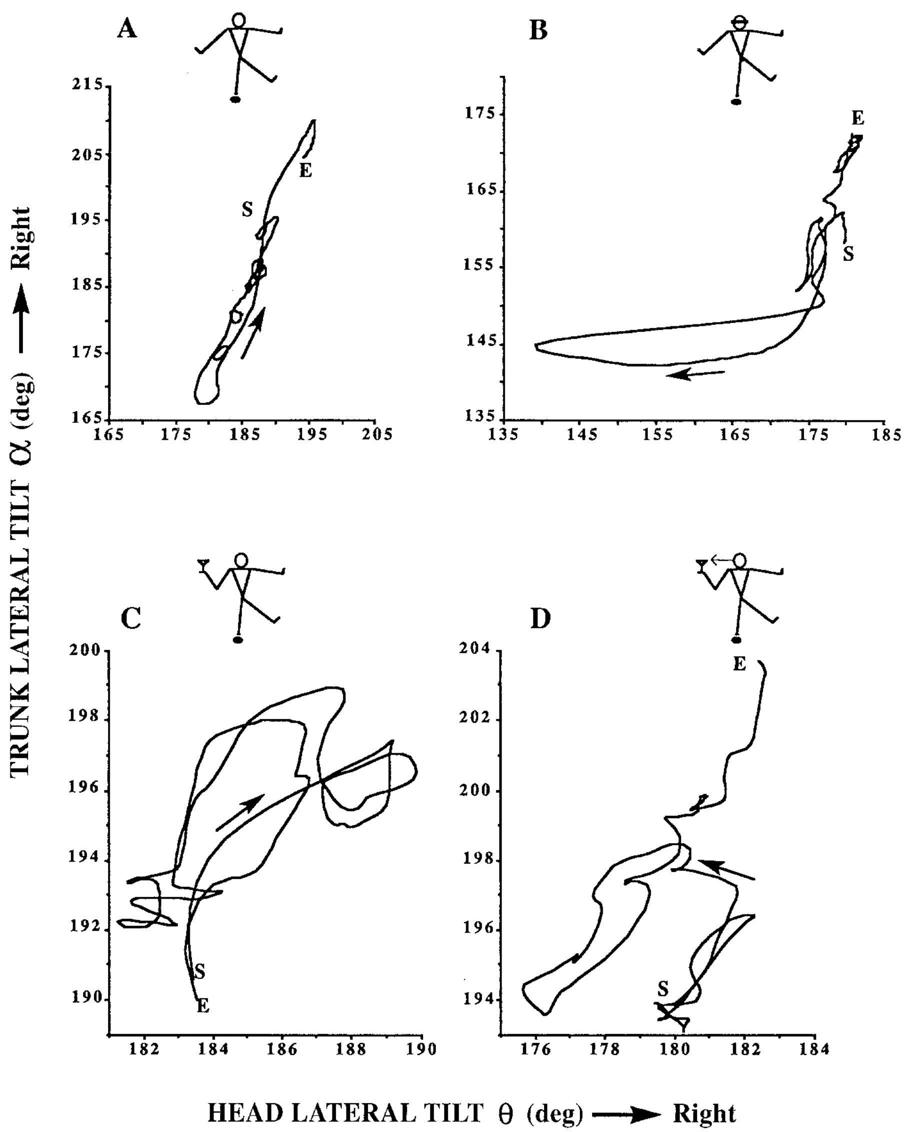

Fig. 7A–E Relationship between head and trunk rotation in the frontal plane on the beam under the four conditions in a single typical subject. The head angular position with respect to the earth vertical (θ) is plotted as a function of trunk angular position (α), during 5 s of recording. Axes are equally scaled. **A** 180° value indicates vertical direction. *S* and *E* indicate, respectively, the start and the end point of the cyclograph. *Arrows* indicate the direction of the movements

Under light conditions the maximum correlation of 0.5 + 0.18 was found with a positive temporal shift of about 20 ms. The positive, short time shift indicates that the movements of the head follow those of the trunk with a very small delay, i.e., almost simultaneously. Statistical analysis of correlation coefficient did not reveal significant differences between all experimental conditions.

When visual information is lacking, the mean value of correlation remains almost the same (0.52+0.20); the time shift between head and trunk movements becomes even shorter (under 20 ms). When subjects hold a cup, the correlation between the rotations of head and trunk is less than under the two previous conditions (0.41±0.20; time shift 35 ms). This decrease corresponds to uncoupling of head and trunk movements in the frontal plane. The same observation can be made when the subject fixed his gaze on the cup. Nevertheless, the amount of correlation increased slightly (0.46±0.14), remaining, however, lower than for unconstrained posture, and the time shift was enhanced by a factor of about 2 (60 ms).

Discussion

Head and trunk references

The present study was designed to reveal head and trunk postural strategies during complex tasks which require fine equilibrium in the frontal plane. The results demonstrate that, in spite of large translations along the lateral axis due to the difficulty of the tasks, head angular displacements in the frontal plane are reduced. In contrast, the trunk, which is more proximal to the support than the head, is generally more stable with regard to translation, but not so stable in lateral tilt. Mean maximum head and trunk angular displacement, velocity, and acceleration values for the beam and the rocking platform are close to these obtained during complex movements (Pozzo et al. 1989). These data extend our previous studies which have shown good head angular stabilization relative to the other limbs in the sagittal plane during locomotion. The results also confirm and generalize this behavior to the frontal plane.

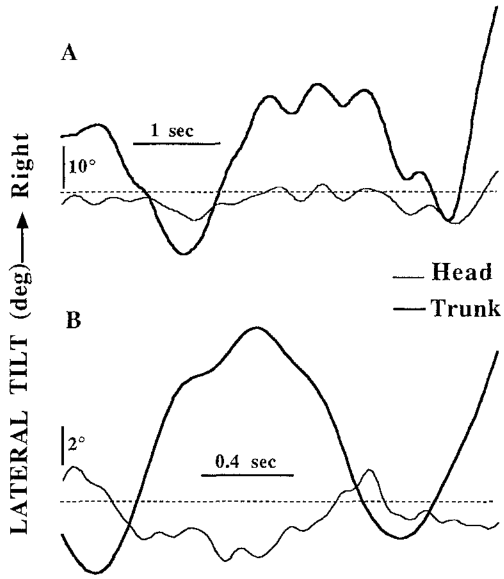

Fig. 8A, B Typical raw data of head and trunk rotation in the frontal plane plotted as a function of time. **A** Note the good correlation between head and trunk angular displacement and head stabilization in spite of the large trunk angular displacement. **B** Trunk rotation in one direction is coupled with head rotation in opposite direction

Comparisons between head and trunk angular displacements during single trials show that the trunk is as stable as the head during small postural oscillations. This latter result suggests that the head, the trunk, or a head-trunk unit could be used to provide a reference for postural control of these tasks. However, complex equilibrium tasks require a minimization of the displacements of the center of gravity (CG), therefore trunk movements must be limited mostly to rotation around the CG. This is incompatible with the stabilization of trunk orientation relative to the vertical, since such stabilization involves translational movements of CG, producing an inevitable fall. In addition, on the beam the trunk must be constantly inclined relative to the vertical in order to compensate the weight of the free leg; this inclination probably compromises the possibility of using the trunk as a reference.

However, the trunk could still serve as a reasonably good reference if:

1. The postural task is simple for a given subject and he can easily keep the body oscillations in a limited range of 1–5°.
2. The subject does not utilize the trunk as an actuator owing to more extensive and efficient use of limbs in maintaining his or her balance (increased mobility of distant links, involving additional degrees of freedom).

In the two above-mentioned cases, the postural strategy may need no additional head stabilization in lateral tilt. If the body rests near the vertical, the "trunk" reference, constructed on the basis of proprioception and tactile information about force interactions between the feet and a support, appears at least as effective as the "head" reference. In addition, if the subject freezes the neck joints and uses a head-trunk unit as a reference, visual information about translations in the frontal plane could be used directly for correction of very small body instabilities.

One can expect, therefore, that the head stabilization strategy would be used preferably by subjects needing to counteract great body oscillations. The more stable subjects could use a head-trunk stabilization strategy. A mixed strategy is also possible: in the same trial the head and trunk often rotate as one unit during small body oscillations, but large and quick trunk inclinations activate the head stabilization mechanism (see Fig. 8A).

The two postural strategies found in our study show that the head, which is always stabilized with respect to gravity, could be considered exclusively as a *reference segment*; otherwise, the trunk can be used either as a reference segment (as on the rocking platform where head and trunk remained oriented vertically) or as an *actuator* for controlling postural equilibrium (as on the beam where the trunk is tilted). These strategies are probably chosen depending on the mechanical and sensorimotor specificities of the tasks and of motor abilities of the subject. Our data suggest that the motor control system has definite limitations which prevent simultaneous use of one segment as both a reference and an actuator.

Postural strategies in the two tasks

The beam, as compared to the rocking platform, provides a postural fixation, and the subject can rely on a pedate control system (where the foot provides a stable support; Fomin and Stillkind 1973). In contrast, on the rocking platform postural fixation is no longer possible because of the continuous movement of the support surface which cannot provide an absolute frame of reference. In this connection, equilibrium maintenance on the rocking platform resembles, for instance, surfing.

On the beam, the monopedal stance on a small, rounded support does not allow the subject to exert large ankle torque in the frontal plane to compensate postural disturbances and the plantar tactile signal cannot be efficiently used on a local level to control equilibrium by means of local reflexes. The results show that the trunk is used as an instrumental component of the equilibrium and that the classic inverted pendulum model in this task can no longer be used to describe postural strategies.

On the rocking platform, despite the bipodal stance, the torques exerted on the support surface are low due to the small surface of contact of the support with the ground. Thus, the movement of the two legs have to be finely coordinated. In most cases subjects try to keep the mean angular position of the trunk near the vertical, while the lower limbs behave like actuators of the head-trunk unit. A similar strategy was observed in locomotion (Pozzo et al. 1990), where lower limbs act as actuators of the stabilized head-trunk unit.

Mechanisms and purpose of head stabilization

As the head serves as a stabilized platform for vision and vestibular sense, one could suggest that visual or vestibular information could be used as feedback source for maintenance of constant head orientation. However, since the time delay between trunk and head movements is very short (about 40 ms), the head stabilization should partially rely on feedforward mechanisms, that is, on the central anticipatory coordination of head and trunk movements. Such coordination, as a part of multijoint synergy directed to compensate postural disturbances, was observed by Gurfinkel et al. (1971) during respiratory movements in the erect posture. One could suppose that the motor command for the active change of trunk orientation is accompanied by a command for head lateral tilt in the opposite direction. Figure 7B shows an example of a record in which large trunk lateral tilt in one direction is coupled with a head rotation in opposite direction; it should be stressed that on this record counter-rotation begins simultaneously with trunk motion or even earlier.

We know from perceptual studies that the perceived gravitational vertical may deviate from the objective vertical by some degrees when the head is tilted in the frontal plane. The deviation of the subjective (or perceived) vertical following lateral head tilt, namely the Aubert (1861) and Muller (1916) effects, could be due to compensatory eye movements in torsion. The results of Balliet and Nakayama (1978), which indicate that changes in ocular torsional position is accompanied by strong changes in perceived body orientation, are in agreement with this suggestion. When the head remains near the vertical while the trunk is tilted, the two effects decrease significantly (Wade 1968).

The effectiveness of graviceptor cues on the perception of vertical is known to decrease when the head is tilted in roll away from the erect position (Schöne and Udo de Haes 1971). Young et al. (1975) attribute this phenomenon to reliance principally on the signals from the utricular otolith to measure head orientation: this organ's sensitivity to changes in head tilt decreases as the cosine of the angle of the head longitudinal axis from the vertical (Ormsby and Young 1976). Furthermore, the inhibition of visually induced static tilt, based upon viewing of static tilted visual scenes, also decreases when the head is moved away from the vertical (Udo de Haes 1970) or inverted (Young et al. 1975).

According to Mittelstaedt (1983), the subjective vertical is computed on the basis of the gravitoinertia vector and the idiotropic vector, which correspond to an egocentric reference based on head and trunk orientation. Parker and Poston (1984) confirm the role of the idiotropic vector for subjective vertical localization. These authors demonstrate that, when head and trunk are oriented differently, there could appear intravectorial conflict, inducing a large shift of subjective vertical with respect to the earth-gravity vertical. Thus, if the head or both the head and trunk are aligned with the vertical, the gravitational or egocentric reference associated with vertical gravity provide a strong spatial invariant used to control postural equilibrium.

Independently of the difference between the visual information about orientation and about movement, the angular stabilization of the cephalic segment simplifies the geometric structure of optical flow, which, according to Stoffregen (1985), is pertinent for the perception of movement. Furthermore, the stabilization facilitates the fusion between the visual information (of the position and movement) and information from otoliths (about gravity or inertial forces).

A fine control of the CG displacements necessitates reliable references which measure both linear and angular displacements of different body parts. The trunk can provide a good reference for limb and head movements, but this reference is only egocentric. During dynamic equilibrium tasks, additional exocentric references are needed to evaluate absolute body position in the ground coordinate system. According to Saltzman (1979) this can be provided by using proprioceptive signals from a kinematic chain linking the trunk with the support. Nevertheless, on the rocking platform this strategy could be too demanding for the *body scheme* system, which in this case must integrate in real time the constantly changing and not always reliable tactile and proprioceptive inputs. It would appear then that visual and vestibular senses would assume greater importance. However, visual and vestibular information is obtained in a head-centered reference system and, in general, must be converted to a ground reference system. For such a complex conversion the CNS needs information about head inclination, this again requiring integration of tactile input from feet and proprioceptive input from lower limbs, trunk, and neck, confronting the body scheme with a previous problem of time constraint. Head stabilization about the vertical may improve postural control, making the transition from one reference frame to another unnecessary and providing the motor control system with two really *independent* sources of spatial information – kinesthetic and visual/vestibular. The availability of independent references would permit the mutual checking of afferent information and much facilitate the integration and fusion of complex multisensory inputs.

Role of vision

Paulus et al. (1984) have shown that central visual information exhibits a powerful contribution to postural control, in particular for lateral sway. Moreover, Brandt et al. (1985) described the instability of patients with visual field defects (e.g., central scotomas in multiple sclerosis) which produce lateral oscillations during balancing on one foot. According to these authors, the particular contribution of the fovea in correcting lateral postural imbalances is due to the threshold for detection of body sway, which is lower for lateral (0.056 cm for an eye-target distance of 1 m) than anteroposterior oscillations (0.37 cm for the same distance). Simple geometrical reasoning explains this difference: the change in retinal size of a viewed object due to fore-aft sway is considerably smaller than the retinal displacement of the object due to lateral head shift of the same magnitude.

However, the present results obtained in darkness seem to contradict the hypothesis about the importance of visual information for the maintenance of lateral equilibrium. In fact, we did not observe significant differences between light and dark conditions. To explain this apparent contradiction it is necessary to recall that, in darkness, subjects have great difficulties in maintaining their equilibrium. We have excluded from the data analysis all trials in which subjects fell before the end of recording. So, one can suppose that those trials in which subjects succeeded in accomplishing the proposed postural task had restricted head and trunk oscillations which did not exceed the limits of head and trunk sway under the conditions of normal vision. Consequently, the values obtained correspond to the maximal amplitude of head and trunk lateral tilt compatible with maintaining equilibrium on the beam. We propose that beyond these ranges the remaining available information (vestibular, proprioceptive, and tactile) is not sufficient to substitute for visual information and to compensate for larger postural instabilities, thus the subject falls down.

In order to verify whether these limiting values are not due simply to mechanical constraints, two subjects were asked to make extensive voluntary head and trunk movements while maintaining their equilibrium on the beam and on the rocking platform in the light. The amplitudes obtained under this condition largely exceeded peak amplitudes obtained in darkness on the beam and on the rocking platform. Otherwise, we found that the falls in darkness were systematically preceded by head angular displacements out of its normal range.

Taken together, these results suggest that: (1) visual information is necessary to compensate for large postural instabilities; and (2) head stabilization can optimize postural control when visual information is lacking.

Influence of the manual task and of the constraint on gaze direction

As can be seen from the corresponding Results section, the additional constraint of holding a cup does not give rise to drastic modification of head and trunk movements. Gaze fixation on the cup also had no profound effect on postural strategy. These results suggest that the stabilization of a peripheral link (hand with cup) and head stabilization probably rely on different mechanisms organized at different levels of motor control. The head (or head-trunk) stabilization could be necessary to provide the motor control system with vertical reference for evaluation of lateral body tilt. If this high-priority aim is successfully achieved, tasks such as hand stabilization or maintaining gaze fixation on the cup can be solved. Control of hand movements or gaze direction is performed in the same spatial reference system as that used for dealing with the complex task of lateral equilibrium. As hand displacements are a result of both changes of arm joint angles and lateral movements of the shoulder articulation with the trunk, hand stabilization can include also a minimization of trunk lateral tilt. Such a tendency to decrease trunk movements under C and G conditions (although not always significant) can be seen in our data. The G condition (additional constraint for central vision) does not significantly deteriorate postural stability as compared to the C condition. So one can suppose that, whether central vision is crucial for constructing visual vertical (as was already suggested above), the necessary references can rely on memory during short episodes when central vision is occupied with other tasks.

Acknowledgements This research was supported by a grant from the Human Frontier Science Program A00023. The authors gratefully acknowledge the contribution of the Centre National d'Etudes Spatiales for providing the equipment needed for this research.

References

Assaiante C, Amblard B (1990) Head stabilization in space while walking: effect of visual restriction in children and adults. In: Brandt T (ed) Xth International Symposium on Disorder of Posture and Gait. Verlag für Medizin, Munich, pp 229–233

Aubert H (1861) Eine scheinbare bedeutende Dehnung von Objekten bei Neigung des Kopfes nach rechts oder links. Virkows Arch 20: 381–393

Balliet R, Nakayama K (1978) Egocentric orientation is influenced by trained voluntary cyclorotary eye movements. Nature 21: 214–216

Berthoz A, Pozzo T (1988) Intermittent head stabilization during postural and locomotory tasks in humans. In: Amblard B, Berthoz A, Clarac F (eds) Development, adaptation and modulation of posture and gait. Elsevier, Amsterdam, pp 189–198

Brandt T, Paulus WM, Straub A (1985) Visual acuity, visual field and visual scene characteristics affect postural balance. In: Igarashi M, Owen Black F (eds) Vestibular and visual control on posture and locomotor equilibrium. Karger, Basel, pp 93–98

Clément G, Jacquin T, Berthoz A (1985) Habituation of postural readjustements induced by motion of visual scenes. In: Igarashi M, Owen Black F (eds) Vestibular and visual control on posture and locomotor equilibrium. Karger, Basel, pp 99–104

Collewijn H, Van der Steen J, Ferman L, Jansen TC (1985) Human ocular counterroll: assessment of static and dynamic properties from electromagnetic sceral coil recordings. Exp Brain Res 59: 185–196

Dichgans J, Held R, Young LR, Brandt T (1972) Moving visual scenes influence the apparent direction of gravity. Science 178: 1217–1219

Droulez J (1988) Topological aspects of sensori-motor control. In: Gurfinkel VS, Ioffe ME, Massion J, Roll JP (eds) Stance and motion, facts and concepts. Plenum, New York, pp 251–259

Droulez J, Berthoz A (1986) Servo-controlled (conservative) versus topological (projective) mode of sensory motor control. In: Bles W, Brandt T (eds) Disorders of posture and gait. Elsevier, Amsterdam, pp 83–97

Droulez J, Berthoz A, Vidal PP (1985) Use and limits of visual vestibular interaction in the control of posture. Are there two modes of sensorimotor control? In: Igarashi M, Owen Black F (eds) Vestibular and visual control on posture and locomotor equilibrium. Karger, Basel, pp 14–21

Fomin SV, Stillkind TI (1973) On the dynamic equilibrium of the pedatar system. In: Gydikov A, Tankov NT, Kosarov DS (eds) Motor control. Plenum, New York

Grossman GE, Leigh RJ, Abel LA, Lanska DJ, Thurston SE (1988) Frequency and velocity of rotational head perturbation during locomotion. Exp Brain Res 70: 470–476

Gurfinkel V, Levik Y (1991) Perceptual and automatic aspects of the postural body scheme. In: Paillard J (ed) Brain and space. Oxford University Press, New York, pp 147-162

Gurfinkel VS, Kots JM, Paltsev FI, Feldman AG (1971) Organization of interarticular interaction as exemplified by compensation of respiratory disturbances in the orthograde posture in man. In: Gelfand IM (ed) Models of the structural functional organization of certain biological systems. MIT Press, Cambridge, Mass, pp 382–395

Horak FB, Nashner LM (1986) Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol 55(6): 1369–1370

Hugon M, Massion J, Wiesandanger M (1982) Anticipatory postural changes induced by active unloading and comparison with passive unloading in man. Pflugers Arch 393: 292–296

Keshner EA, Cromwell R, Peterson B (1992). Head stabilization during vertical seated rotations and gait. In: Woollacott M, Horak F (eds) Posture and gait: control mechanisms. University of Oregon, Portland, pp 105–108

Marsden CD, Merton PA, Morton HP (1981) Human postural responses. Brain 104: 513–534

Mauritz KH, Dichgans J, Hufschmidt A (1977) The angle of vision roll motion determines displacement of subjective vertical. Percept Psychophys 22: 557–562

Mittelstaedt H (1983) A new solution to the problem of the subjective vertical. Naturwissenschaften 70: 272–281

Mouchnino L, Aurenty R, Massion J, Pedotti A (1990) Coordinated control of posture and equilibrium during leg movement. In: Brandt T (ed) Xth International Symposium on Disorder of Posture and Gait. Verlag für Medizin, Munich, pp 68–72

Muller GE (1916) Über das Auberstch Phänomen. Z Sinnesphysiol 49: 109–244

Ormsby CC, Young LR (1976) Integration of semicircular canal and otolith information for multisensory orientation stimuli. Math Biosci 34: 1–21

Parker D, Poston RL (1984) Tilt from a head inverted position produces displacement of visual subjective vertical in the opposite direction. Percept Psychophys 36: 461–465

Paulus M, Straube A, Brandt T (1984) Visual stabilization of posture. Brain 107: 1143–1163

Pozzo T, Berthoz A, Lefort L (1989) Head kinematic during various motor tasks in humans. Prog Brain Res 80: 377–383

Pozzo T, Berthoz A, Lefort L (1990) Head stabilization during various locomotory tasks in humans. I. Normal subjects. Exp Brain Res 82: 97–106

Pozzo T, Levik Y, Berthoz A (1992) Head and trunk coordination in the frontal plane during complex equilibrium tasks. In: Woollacott M, Horak F (eds) XIth International symposium on posture and gait: control mechanisms. University of Oregon, Portland, pp 97–100

Saltzman E (1979) Level of sensorimotor representation. J Math Psychol 20: 91–163

Schöne H, Udo de Haes H (1971) Space orientation in human with special reference to the interaction of vestibular, somaesthetic and visual input. In: Drischel H, Tiedt N (eds) Biokybernetik. Fischer, Jena

Shupert CL, Black O, Horak FB, Nashner LM (1988) Coordination of the head and body in response to support surface translations in normals and patients with bilaterally reduced vestibular function. In: Amblard B, Berthoz A, Clarac F (eds) Development, adaptation and modulation of posture and gait. Elsevier, Amsterdam, pp 281–289

Stoffregen TA (1985) Flow structure versus retinal location in the optical control of stance. J Exp Psychol 11: 554–565

Udo de Haes H (1970) Stability of apparent vertical and ocular countertorsion as a function of lateral tilt. Percept Psychophys 8: 137–142

Wade NJ (1968) Visual orientation during and after lateral head,body and trunk tilt. Percept Psychophys 3: 215–219

Young LR, Oman CM, Dichgans J (1975) Influence of head orientation on visually induced pitch and roll sensations. Aviat Space Environ Med 46: 264–268