ORIGINAL RESEARCH

Effects of Hypobaric Hypoxia on Postural Control

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Background: While the effects of accelerative forces on the vestibular system have been thoroughly investigated, the effects of hypobaric conditions on the postural system have attracted less attention. The purpose of the study was to investigate if postural control is affected by hypobaric hypoxia. ***Hypothesis:*** Moderate hypobaric hypoxia may reduce postural control. ***Methods:*** Subjective and multiple objective measurements of postural control with open and closed eyes were made in 16 military aircrew standing on a static balance platform before, during, and after exposure to an altitude chamber training profile with a maximum altitude of 25,000 ft. ***Results:*** No subjective dizziness and no clinical unsteadiness were noted. However, significant changes in body sway were found at the balance platform during hypobaric exposure at 18,000, 14,000 and 8000 ft compared with the baseline registrations. The relative increase in sway movements was greater in the eyes open condition compared with the eyes closed condition, and significant for movements in the anteroposterior plane but not in the lateral plane. Most sway parameters returned to pre-exposure values on return to ground level. ***Conclusions:*** Acute hypobaric hypoxia, corresponding to the tested altitudes, influenced postural control primarily in the anteroposterior plane with eyes open. This is in agreement with other studies showing that vision is the first of the special senses to be altered by lack of oxygen.

SPATIAL DISORIENTATION (SD) is a major problem in aviation. All aircrew may experience SD because the human sensory system is adapted to a firm, stationary environment. While the effects of accelerative forces on the vestibular system have been thoroughly investigated, the effects of hypobaric conditions on the postural system have attracted less attention. More knowledge concerning postural control during hypobaric hypoxia may help to extend our understanding of problems related to SD in flight.

Hypobaric conditions affect all parts of the human organism. Such effects on different sensory systems may give rise to potentially dangerous situations because of increased SD. The postural system may be influenced through multiple mechanisms during flight: large variations in acceleration forces, asymmetric middle ear pressure, inner ear barotrauma, hypoxia, sensory deprivation, visual illusions, impairment of night vision, breathing gas impurities, motion and space sickness, the possible formation of vascular or peri- and endolymphatic microbubbles, and decompression sickness. Several of these mechanisms are still incompletely understood, and are subject to ongoing investigations.

The postural system is highly complex, including feedback loops from several sensory qualities, such as the vestibular system, vision, proprioception from joints, tendons and muscles and superficial and deep tactile sense communicating with the central nervous system (CNS).

The vestibular system plays a central role in maintaining postural control and keeping track of body position, as well as keeping an image stationary on the retina. In the air or in space when other sensory stimuli, such as vision, proprioception, and tactile sense, may be altered, or even missing, misleading information from the vestibular system itself is often the main cause of SD.

Attempts have been made to examine the effects of hypobaric exposure on the inner ear function in man and in animals (4,8,12,14,15,17). Complaints of dizziness have been reported by subjects at altitudes as low as 10000 ft (16). In one study a decrement in postural control during mild hypobaric hypoxia was reported on subjects tested on a force platform at 5000, 8000 and at 10000 ft (8), while no decrement was observed at 12000 ft. It was concluded that postural control mechanisms, as an integrative functional unit, are very sensitive to exposure to acute, mild hypoxia. The lack of influence on postural control at 12000 ft was explained by possible compensatory mechanisms that first became effective at this degree of hypoxia (8). However, postural sway, as observed on a force platform, has in another experiment been reported to increase markedly at 19685 ft (17). Several reports of postflight decrement in the postural control function after manned spaceflights have also been published (4,10,11). The mechanisms behind these results are difficult to compare and seem equivocal. More systematic studies are therefore needed to reveal if hypoxia, hypobaria, or a combination of these two factors are responsible for the observed changes.

A static balance platform offers a simple, quantitative and reproducible method for evaluating the postural sys-

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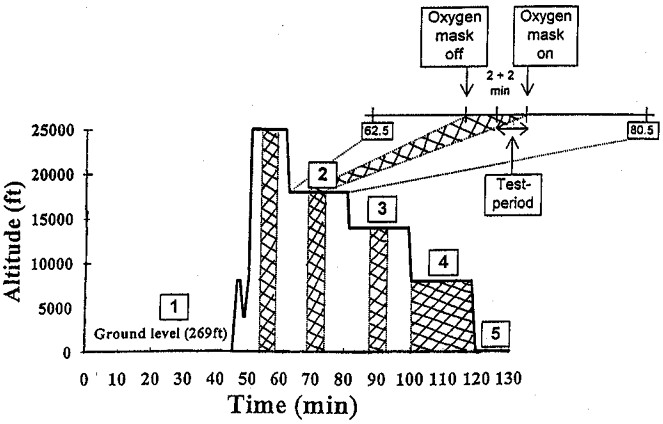

Fig. 1. The profile of the hypobaric chamber flight simulation. The scattered area indicates the "off oxygen" period.

tem, and has also been used for the evaluation of postural control under hyperbaric conditions (1–3,13).

Our objective was to investigate if hypobaric hypoxia, which may occur during loss of cabin/cockpit pressure at service altitude for passenger and military aircraft, will reduce postural control in the brief period of time needed for descent to safe altitude without the use of extra oxygen.

METHODS

The present investigation was a joint project between the University Hospital of Bergen, the Royal Norwegian Air Force (RNoAF) Institute of Aviation Medicine, and the Royal Norwegian Navy. The experiment was performed during a refresher course in Aviation Medicine at the RNoAF Institute of Aviation Medicine, and we had to adapt our test protocol to the routines of the institute.

All 16 subjects were RNoAF aircrew, 6 fighter pilots including 1 female, and 10 pilots, navigators and other crewmembers on large transport and maritime surveillance aircraft, 24–46 (mean 30) yr of age. Informed consent to attend the experiment was obtained from all subjects prior to testing, including their right to withdraw at any time. The project was approved by the Norwegian Regional Research Ethics Committee.

The Chamber Simulation

After a pre-exposure balance test in the chamber at ground level (270 ft), all subjects were preoxygenated for 45 min and continued breathing 100% oxygen during the chamber test, except when removing their oxygen mask during individual hypoxia exposure and balance testing. The experiment was performed at the tail end of a standard aircrew altitude chamber training profile. Two chamber flights, each with eight subjects, were performed. The U.S. Standard Atmospheric Pressure Table was used to approximate the equivalent altitudes from the actual pressures. The profile is illustrated in **Fig. 1** and consisted of a rapid ascent to 8000 ft followed by a 4000 ft $\cdot$ min^{-1} descent to 4000 ft to check for possible ear and sinus problems. The chamber was again taken to 8000 ft, followed by a rapid decompression to 22,500 ft in 10 s, and a further ascent to 25,000 ft in 30 s. At this altitude individual hypoxia testing for training purposes was performed, all subjects removing their oxygen masks for 2–5 min while performing paper and pencil tests and psychomotor tests. After 11 min at 25,000 ft, the chamber altitude was lowered to 18,000 ft where all subjects performed their first balance test under hypobaric conditions. Each subject removed the oxygen mask 2 min prior to testing, and resumed oxygen breathing only after the 2-min balance test was completed. Accordingly, each subject was off oxygen for 4 min at each test altitude above 10,000 ft. After 18 min, the chamber altitude was reduced to 14,000 ft for the next balance test, following the same procedure. After another 18-min period, testing was repeated at 8000 ft and finally at ground level. Use of oxygen mask was discontinued below 10,000 ft. The whole protocol lasted approximately 2.5 h.

Computerized stabilometry (posturography) used for documenting balance performance, is non-invasive and causes no discomfort. In our study the aircrew were instructed to stand quietly with their feet 7 cm apart and the arms at their sides on a static balance platform, for 1 min with the eyes open looking at a small eye-level target 2 m away, and for 1 min with the eyes closed. The first eight subjects had their eyes open at first and then closed, while the last eight subjects in the second chamber flight had the test sequence in the opposite order. No training and only minimal instruction was needed. The test was conducted under visually and acoustically standardized conditions in the same altitude chamber on all aircrew.

All subjective complaints of dizziness were noted by an observer and each test subject was observed while the test sequences took place on the balance platform.

A balance platform (Cosmogamma©, Via Zalloni, 40066 Pieve di Cento, Bologna, Italy), measuring 40 × 40 × 8 cm, was used for data collection. The shift of the body's center of pressure (COP) at the soles of the feet during body sway was sensed by three mechanical-elec-

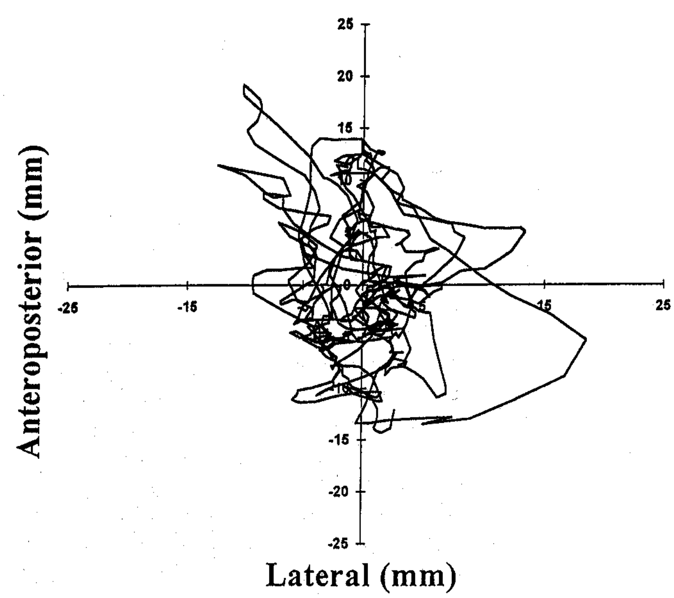

Fig. 2. A 60-s center-of-pressure trajectory in the lateral and anteroposterior plane.

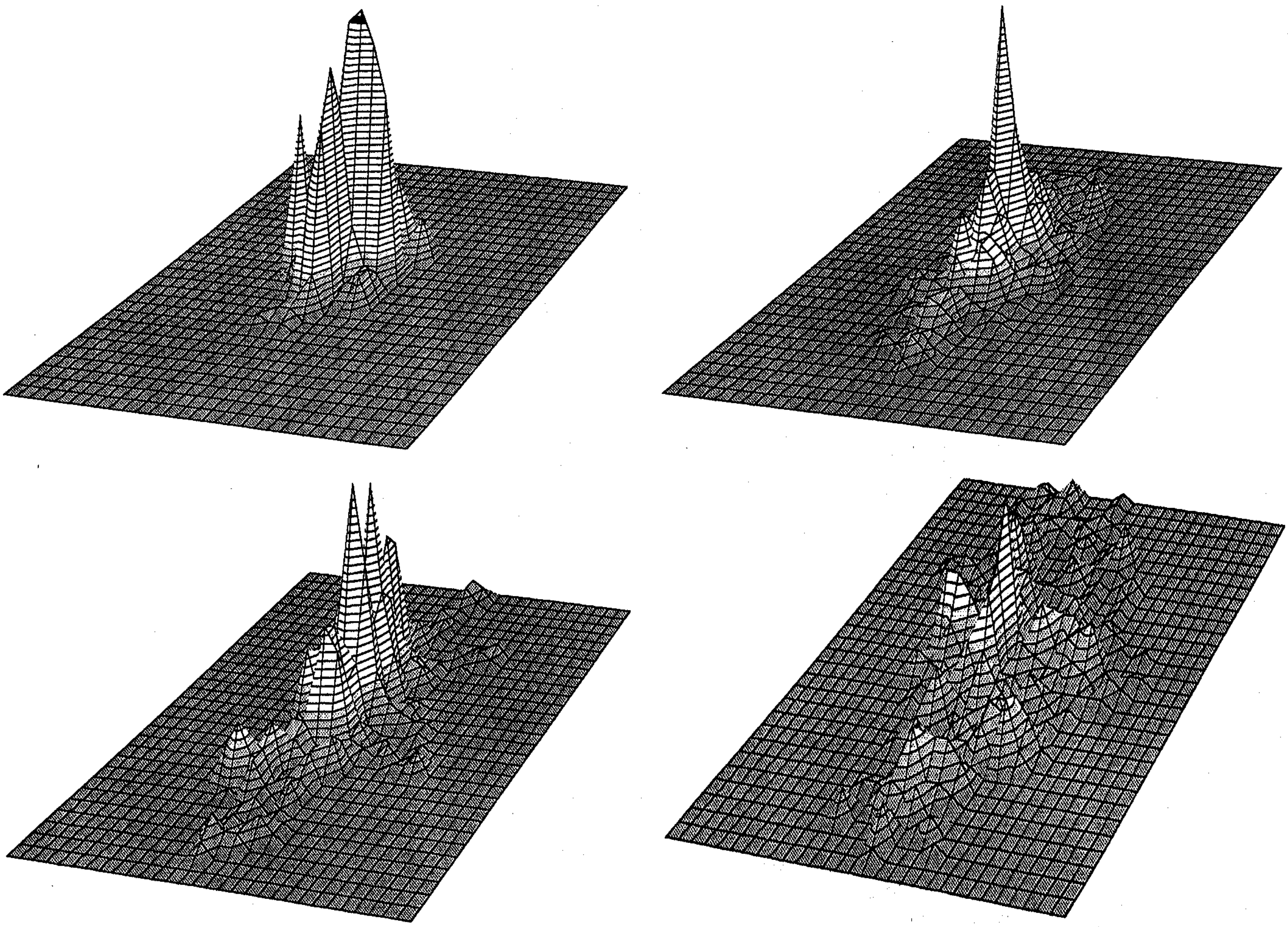

Fig. 3. The distribution of the sway vector for one of the pilots in the folowing conditions: a. (upper left) Ground level with eyes open; b. (upper right) Ground level with eyes closed; c. (lower left) At 18,000 ft with eyes open; d. (lower right) At 18,000 ft with eyes closed. X-axis: lateral plane; Y-axis: anteroposterior plane; Z-axis: numbers of sway vectors. Peak heights indicate total numbers of the same vector.

trical transducers (strain gauges) in the platform. The signals were relayed by cable through a penetrator in the chamber wall to a computer (12 bit A/D resolution and 10 Hz sampling frequency) outside the altitude chamber. A monitor screen provided graphic and numerical presentations of different body sway characteristics, such as shift of the COP in the anteroposterior and lateral planes (**Fig. 2**).

To characterize the COP-variable, we applied different sway parameters for measuring the amplitude and speed of sway performed by the subject while standing on the platform. These were the COP's mean sway speed, maximum and mean sway amplitude, sway frequency in the anteroposterior and lateral planes and time spent by the COP within circles with different diameters. Since some of these parameters reflected the same postural stability change, we chose a few parameters, which are commonly used in a clinical context, for more detailed analyzes.

The path length the COP described during each 1-min registration is determined by the gravitational force and the isometric muscular contractions, and thus related to the effort of the balance system in maintaining an upright posture. The mean speeds of the correction movements in the anteroposterior and lateral planes were chosen to evaluate the postural stability in the two planes.

The Romberg index (RI) is the ratio between measured parameters with closed and open eyes. It can be calculated for different parameters such as the path length and the speed described by the COP. Usually, body sway will increase when closing the eyes, causing a detectable deterioration in performance. Accordingly, the RI will usually have a numerical value > 1.

Within subjects analysis of variance (ANOVA) with repeated measures was used to examine the various parameters describing the effect of hypobaric hypoxia on

TABLE I. REPEATED MEASURES ANOVA WITHIN SUBJECTS EFFECT AT DIFFERENT ALTITUDES.

	F(4, 60)	p
Path length (EO)	4.57	0.003
Path length (EC)	3.47	0.013
Path length (RI)	5.45	0.001
Lateral speed (EO)	1.80	0.140
Lateral speed (EC)	2.48	0.054
Lateral speed (RI)	1.38	0.253
AntPost speed (EO)	4.39	0.004
AntPost speed (EC)	3.16	0.020
AntPost speed (RI)	2.62	0.044

EO: Eyes open; EC: Eyes closed; RI: Romberg index.

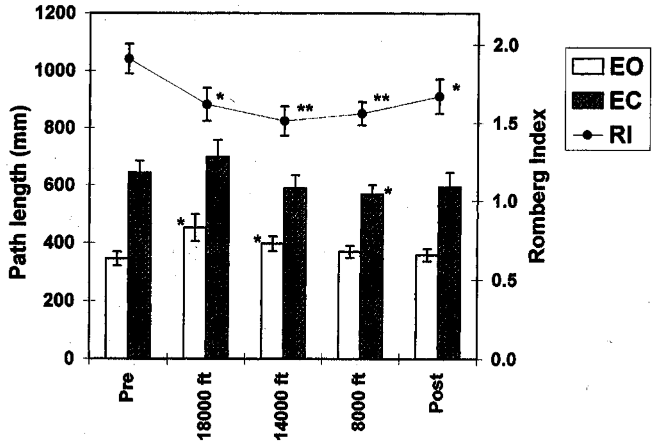

Fig. 4. The path length and Romberg index (RI) at the different altitudes. Mean values, SE and p-values are given. *$p < 0.005$; **$p < 0.00005$. EO = eyes open; EC = eyes closed.

the postural system. When statistical significance was found ($p < 0.05$), two-tailed Student's *t*-tests for paired data were applied to evaluate the difference between the registrations at each altitude and the baseline registration. A single exposure protocol, as published earlier (13), is statistically sufficient when using paired *t*-test for repeated measures.

RESULTS

During balance platform tests at altitude, none of the subjects reported any subjective dizziness and no unsteadiness was noted by the observer. However, balance platform registrations showed changes in body sway both with the eyes closed and open compared with pretest values, and the deterioration was relatively larger when the eyes were open. The increased postural instability was reflected in different parameters characterizing the body sway.

Fig. 3 shows an example of the distribution of the sway vectors for one of the subjects at ground level with the eyes open (Fig. 3a) and closed (Fig. 3b), and at 18,000 ft with the eyes open (Fig. 3c) and closed (Fig. 3 d). The "landscapes" are the histograms of the COP sway vectors in the x-y-plane (c.f. Fig. 2). Peak heights indicate total numbers of the same vector. The pretest recordings with eyes open had highest peak and smallest area of distribution. At 18,000 ft, the peaks became lower while the distribution became larger, mainly in the anteroposterior direction.

The ANOVA statistics for repeated measures at different altitudes are summarized in **Table I.** Statistical significance ($p < 0.05$) was found for path length and anteroposterior speed for both the eyes open and eyes closed condition and for the corresponding RI. No significance was found for mean speed in the lateral plane.

In **Fig. 4**, the mean path length for all 16 subjects, with eyes open and eyes closed, described by the COP at different altitudes, is shown. In the eyes open condition the path length was significantly increased more than 31% at 18,000 ft and approximately 15% at 14,000 ft, compared with the pre-exposure test (**Table II**). In the eyes closed condition the increase was not significant at any altitude. The RI of the path length showed a distinct decrease during exposure to 18,000, 14,000 and 8000 ft. This indicates a deterioration of the relative stability with eyes open compared with the eyes closed condition when exposed to hypobaric hypoxia.

The mean speed of the correction movements in the anteroposterior plane is presented in **Fig. 5**. With eyes open a significant increase of more than 35% for the registration at 18,000 ft and approximately 18% at 14,000 ft compared with pretest values was found (**Table III**). For the eyes closed condition no significant differences were found for the various altitudes compared with preexposure tests. The RI of the mean speed of the correction movements in the anteroposterior plane was significantly reduced for the registrations at 18,000 and 14,000 ft, compared with preexposure values.

DISCUSSION

The incidence of accidental decompression of the pressure cabin in commercial aircraft throughout the world is in the order of 30–40 per yr (6). However, in military peacetime flying, the incidence is much higher. About 2–3 unplanned decompressions per 100,000 flying hours have been recorded for many years (6). Normally a pilot will descend to a safe altitude immediately after loss of cockpit pressure. However, insidious loss of cabin pressure may not always be readily detected, causing delay in the decent procedure.

Our investigation is of a basic physiological nature and it is not directly suitable for making conclusions regarding postural control in seated pilots who take the aircraft down to a safe altitude within a few minutes of loss of cockpit pressure. Since no standard method for testing postural control in seated subjects is available, we have used a static posturography platform for standing subjects. A seated person enjoys substantially greater postural support. Accordingly, it would seem reasonable

TABLE II. PAIRED STUDENT'S *t*-TEST FOR THE DIFFERENCE IN PATH LENGTH AT THE VARIOUS ALTITUDES AND PRETEST.

	Pre		18,000 ft			14,000 ft			8000 ft			Post		
	Mean	SE	Mean	SE	p	Mean	SE	p	Mean	SE	p	Mean	SE	p
EO	345.13	24.28	451.19	46.61	0.029	396.50	25.37	0.016	369.31	20.53	NS	358.50	21.64	NS
EC	642.31	42.05	698.56	58.68	NS	588.63	46.21	NS	567.31	33.61	0.04*	593.56	50.55	NS
RI	1.91	0.09	1.62	0.11	0.027*	1.51	0.09	0.000054*	1.56	0.07	0.000032*	1.67	0.11	0.026*

Mean: Mean value at the various altitudes; SE: Standard error; p: Paired Student's *t*-test for the actual altitude and the pretest.
EO: Eyes open; EC: Eyes closed; RI: Romberg index; NS: Not significant at $\propto = 0.05$. * Decreased value compared to pretest.

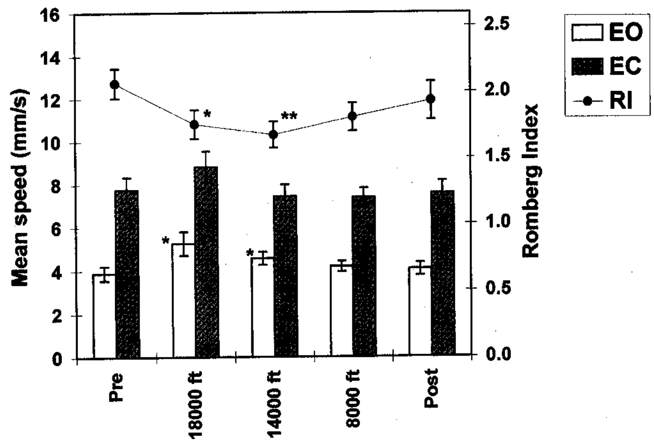

Fig. 5. The mean speed in the anteroposterior plane and Romberg index (RI) at the different altitudes. Mean values, SE and p-values are given. *$p < 0.05$; **$p < 0.001$. EO = eyes open; EC = eyes closed.

that effects of hypoxia would be less for a seated individual. Further, no data are available to correlate standing performance directly with seated performance.

Although our present investigation demonstrated that the postural control became disturbed under acute hypobaric hypoxia, almost all values returned to normal when the ambient pressure returned to baseline. This differs from the effects of CNS toxic substances, e.g., alcohol (7) and anesthetics (9), which can induce measurable aftereffects, but is in accordance with our earlier findings after hyperbaric exposure (13). In that investigation reduced postural control was detected by the balance platform method from approximately 200 msw and deeper, with return to pre-dive values after surfacing. At depth the atmosphere was hyperoxic, so we do not know whether the effects were caused by increased pressure (High Pressure Neurological Syndrome), oxygen toxicity or other mechanisms. The present investigation is one in a series where the separate effects of hypoxia and hypobaria as well as the combination of these will be addressed.

The subjects were only off oxygen for 2 min before and during each 2-min balance testing sequence at altitudes above 10,000 ft (Fig. 1). No extra oxygen was given below 10,000 ft. We did not measure the blood oxygen saturation of the subjects. Thus, the degree of hypoxia is unknown, but above 10,000 ft none of the subjects was in a state of stable hypoxia. Unpublished observations we have made in a stable state of hypoxia at 14,000 ft for 1 h do not indicate that this relatively low altitude together with hypoxia is sufficient to give significant changes in postural control. The combination of higher altitudes and hypoxia seems to be more potent for decreasing postural control. However, we will address this question in more detail in a separate work to be published later.

In the present study, the postural instability increased relatively more with eyes open than with eyes closed at altitude. Accordingly, the RI for most of the observed parameters decreased significantly at altitude. In contrast, we found in a previous investigation that postural instability increased equally in both eyes closed and eyes open conditions when the subjects where exposed to higher ambient pressure (13). We have found the RI useful also when investigating patients with balance problems in a clinical setting.

Our investigation cannot determine which part of the postural system that is affected during hypobaric hypoxia. However, since the vestibulo-cerebellar part of the balance system plays a central role in the maintenance of posture, it may be speculated that this system could be the main site of disturbance. However, vision is the first of the special senses to be altered by lack of oxygen (5). This may explain why we found relatively greater disturbances with eyes open compared with eyes closed at altitude. This may also explain why there was no difference between the eyes closed/open condition in our hyperbaric study where the oxygen partial pressure was increased (13).

The relative increase in sway was higher in the anteroposterior plane than in the lateral plane. This could probably be explained by the anatomical fact that hip and ankle joints are freer for movements in the anteroposterior than in the lateral plane and that the visual corrective input is greater in the lateral plane.

CONCLUSIONS

Acute hypobaric hypoxia at 18,000, 14,000 and 8000 ft influences postural control. Computerized stabilometry is a convenient method for monitoring these changes. It is more sensitive than clinical observation alone and provides objectively quantifiable data.

The relative increase in sway movements was higher in the anteroposterior plane than in the lateral plane. Relative decrement in postural control at the tested altitudes, compared with ground level, was greater with the eyes open than with the eyes closed. One of the reasons for the deterioration of postural control being most prominent with eyes open compared with eyes closed, may be the fact that vision is the first of the special senses to be altered by lack of oxygen.

TABLE III. PAIRED STUDENT'S *t*-TEST FOR THE DIFFERENCE IN MEAN SPEED IN THE ANTEROPOSTERIOR PLANE AT THE VARIOUS ALTITUDES AND PRETEST.

	Pre		18,000 ft			14,000 ft			8000 ft			Post		
	Mean	SE	Mean	SE	p	Mean	SE	p	Mean	SE	p	Mean	SE	p
EO	3.88	0.33	5.25	0.54	0.019	4.56	0.30	0.022	4.19	0.25	NS	4.06	0.30	NS
EC	7.75	0.59	8.81	0.73	NS	7.44	0.55	NS	7.38	0.45	NS	4.06	0.30	NS
RI	2.07	0.11	1.76	0.11	0.038*	1.68	0.10	0.001*	1.81	0.11	NS	1.934	0.14	NS

Mean: Mean value at the various altitudes; SE: Standard error; p: Paired Student's *t*-test for the actual altitude and the pretest.
EO: Eyes open; EC: Eyes closed; RI: Romberg index; NS: Not significant at $\alpha = 0.05$. * Decreased value compared to pretest.

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