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EFFECTS OF WHOLE-BODY VIBRATIONS ON PERCEPTION AND CONTROL OF POSTURE AND MOVEMENT

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ABSTRACT :

Recent studies have described sensory-motor function alterations resulting from vibrations applied to various parts of the body. Our work was aimed at defining the extent of postural and movement control alterations due to vibrations of frequency and amplitude similar to those encountered in cruising helicopters.

Standing and seated Subjects were vibrated at 18 Hz and ± 0.2 to ±0.5g by means of a hydraulic jack. Per- and post-stimulus effects on posture were evaluated through stabilometric recordings which showed a significant shift in mean resting posture and an increase of equilibrium oscillation amplitude. Vibrations were also seen to affect programing and execution of sensory motor controlled tasks. Selective application of vibrations to various parts of the body allowed us to propose the proprio muscular system as the major site of stimulus action.

Electrically (H) and mechanically (T) induced spinal reflexes were analysed during and after vibrations applied to seated Subjects. Both reflexes were deeply depressed and the effects outlasted the duration of the vibration.

Physiological and behavioral effects induced by vibrations under laboratory controlled conditions bring some understanding of the sensory-motor function alterations reported by helicopter pilots and passengers. Suggestions may be proposed to prevent vibrations from reaching the body vibration-sensitive sites and to keep the noxious stimuli from inducing alterating effects on posture and movement control.

I. INTRODUCTION

As part of the programme of cooperation between the universities and industry, the Aerospatiale Helicopter Division asked the Psycho-physiology Laboratory in the University of Provence to investigate as one research topic the effects of low-frequency vibrations on human behaviour. This paper gives the results of this research.

In helicopters as in other modern vehicles , vibrations are transmitted to pilots and passengers through solid contacts such as the seat (arm rest, back and bottom cushions), the command levers and the floor. Though local resonances may persist, a generalized high frequency filtering occurs through skeletal and muscular masses (Hornick, 1973). Recent research has demonstrated the extent of sensory-motor alterations due to such vibrations (Berthoz, 1971; Hornick, 1973; Jex and Magdaleno, 1978). Most alterations affecting postural and locomotion equilibrium, or manual digital control are particularly important during vibrations but may persist minutes after. Vibration signals enter the neurological network through cutaneous, muscular, articular (Hagbarth and Eklund, 1966; Talbot et al., 1968; Burke et al., 1976; Roll et al., 1980), visceral (Tyler and Bard, 1949) or vestibular (Young, 1969) sensory receptors resulting in neurological noise, sensory-motor system errors, discomfort and hazards.

The goals of the present study were, first, to quantify the effects of long term vibration on postural equilibrium and postural adjustments (posture experiments); second, to observe the effects of vibration on the performance of tasks requiring force, velocity and position control (sensory motor experiments) and third, to identify the neurophysiological mechanisms most likely to be responsible for the observed alterations. Postural forces as monitored by a posturograph were need to characterize the effects of vibration on standing S's equilibrium performance. The effects of vibration on sensory-motor system performance were studied in terms of tracking precision and force control. The tasks consisted respectively of tracking a visual target or repetitively producing or maintaining a given force in an isometric situation. The performance during and after vibration was evaluated in terms of precision criteria and compared to pre-vibration readings.

II - METHODS

1. Posture study.

Standing and seated Subjects (Ss) were vibrated at 18Hz and ± 0.5g as measured at platform level, by means of a hydraulic jack. Per- and post-vibration effects on postural equilibrium were evaluated by comparing stabilometric recordings.

Post-vibration experiments : in a first series of experiments - to be referred to as post-vibration experiment - 10 Ss ranging in age from 18 to 46 years were vibrated while in a seated position for 30 minutes at 18 Hz and 0.5g at platform level (Fig. 1).

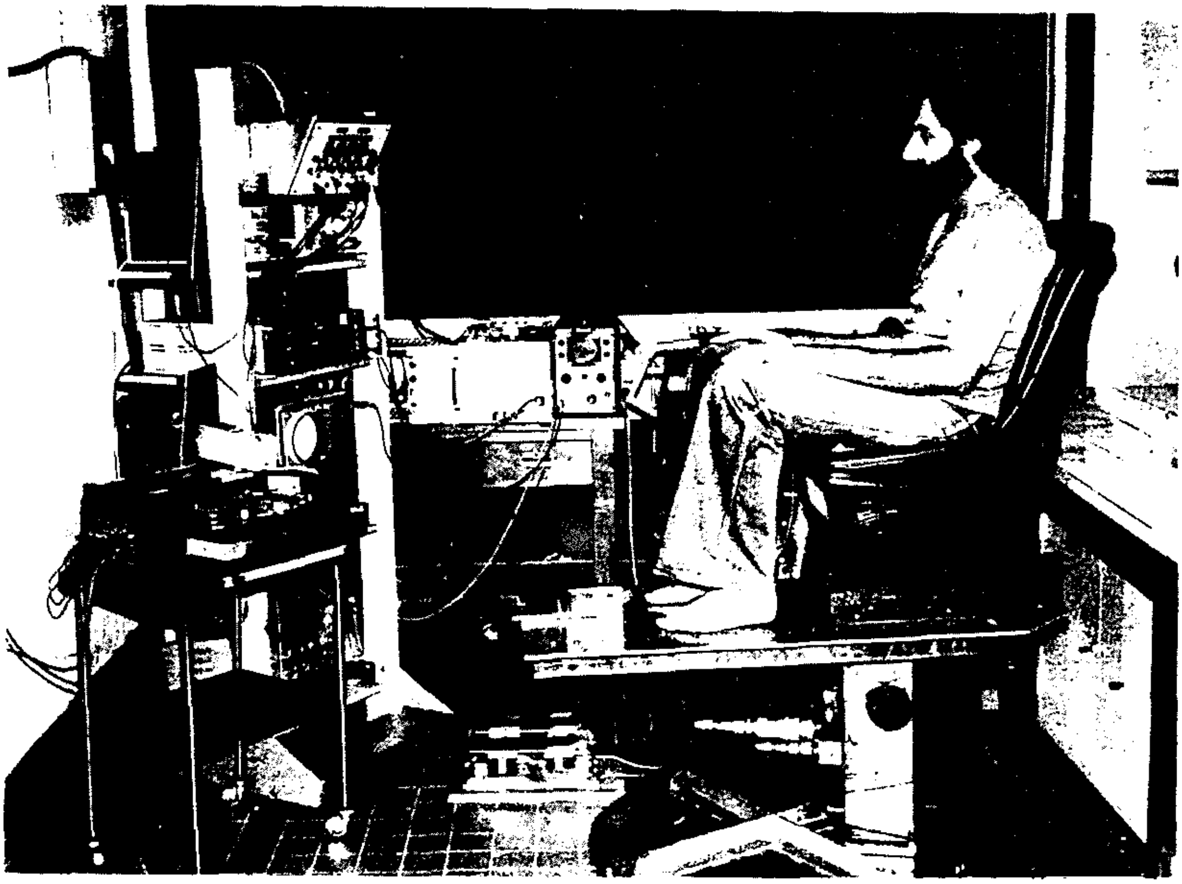

Fig. 1 - Experimental set-up.

Vibrations produced by hydraulic jack were applied to seated Ss or to body segments. After 30 minute periods of vibration, Ss were tested on the stabilometer placed on the floor next to the vibrating platform.

This produced, for a given S, accelerations of ± 0.18g, ± 0.065 and ± 0.1g at knee, thorax and forehead levels respectively. These may appear to be higher values than those commonly encountered on modern helicopters. The choice of ± 0.5g at platform level was the result of a compromise between vibration amplitude and stimulation duration to attempt to simulate the effects of a 2 to 3 hour helicopter flight. The Ss were successively submitted to four experimental conditions consisting of applying vibration either to the whole-body (WBV), the legs (LV), the head and the trunk (HTV) or the head alone (HV). The Ss were tested prior, immediately after and 30 minutes after the end of the 30 minute vibration period. Each test consisted of 6 successive postural trials, each made of a 30 second period of erect standing on the stabilometer (next to the hydraulic jack in Fig.1). The task was simply to remain still around the same trial to trial resting position. Successive trials were separated by 15 second intervals during which the S stepped slowly off the measuring platform and after 2 to 3 seconds stepped back for the next trial.

Per-vibration experiments : the per-vibration effects on posture equilibrium were studied in a group of six Ss who were tested in a standing position. For that purpose, the stabilometer was mounted on the vibrating platform. The S's posture was continuously monitored during five minute periods consisting of one minute control tests before, during and after a three minute vibration period. In some trials, Ss with closed eyes were required to execute a task consisting of swaying their body around the ankle joint so as to produce a three centimeter head displacement at nose level. Sufficient practice was allowed until performance stabilization was reached. Sways were to be executed repeatedly during the five minute trials. The effects of vibrations on posture voluntary control were evaluated in terms of sway amplitude variations as measured by the postural force signals.

2. Movement control study.

Both tracking and force control situations are illustrated on Fig. 2. In tracking tasks, the target was a spot of light moving on the screen in a horizontal direction (foot and hand tracking task). Potentiometric devices monitoring foot or arm position were used to control the position of a second spot. The target spot moved sinusoidally at a frequency of 0.2 Hz. The total excursion was about 10° as seen by the S's eye. Superposition tracking of the target spot required foot and hand rotations of 10° and 30° respectively.

Force tasks consisted of applying pressure with the foot, on a rigid pedal equiped with strain gauges (Fig.2).The S was instructed to produce force steps of 2 sec in duration followed by 2 sec rest. Three levels of force were used. When the performance was stabilized for a given force level, vibration was applied while the S continued the task. The effects of vibration were evaluated in terms of force step maximum amplitude and stability.

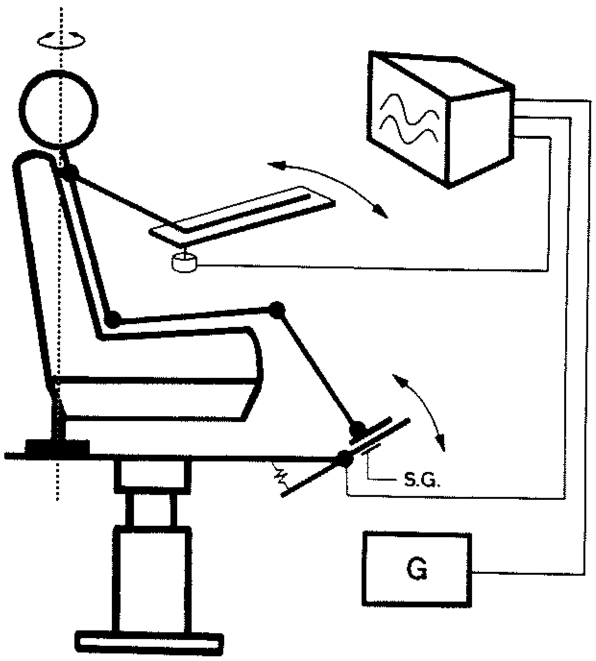

Fig. 2 - Effects of vibration on motor control.
The drawing illustrates manual and foot tracking of a visual target presented on a screen. The force tasks executed blindfolded consisted of exerting given pressures on a rigid foot pedal.

III - RESULTS

Vibrations in the intensity range, occasionally encountered on cruising or landing helicopters for short periods of time such as 0.25 to 0.5g at floor level, induced significant postural force and movement control, mechanism alterations as demonstrated in the sequel.

1. Posture study.

. During vibration in the per-vibration experiments and after vibration in the post-vibration experiment, Ss reported to experience a feeling of perfect stability and of easiness to maintain steady posture with eyes closed. This was especially evident in the first trial directly following WBV and LV and during vibration postural trials which paradoxically were seen to induce major alterations of postural mechanisms. The sensation of "postural comfort" vanished shortly after stimulus cessation.

Post-vibration motor effects : Whole-body and leg vibrations produced a significant alteration in postural regulation mechanisms. Posturograms such as that of Fig. 3 allow an evaluation of the extent of the post-vibration effects. Part A shows a typical 30 second posturogram recorded prior to vibration. Part B shows force signals recorded during the first 30 second post-vibration trial. Anteroposterior and lateral position and

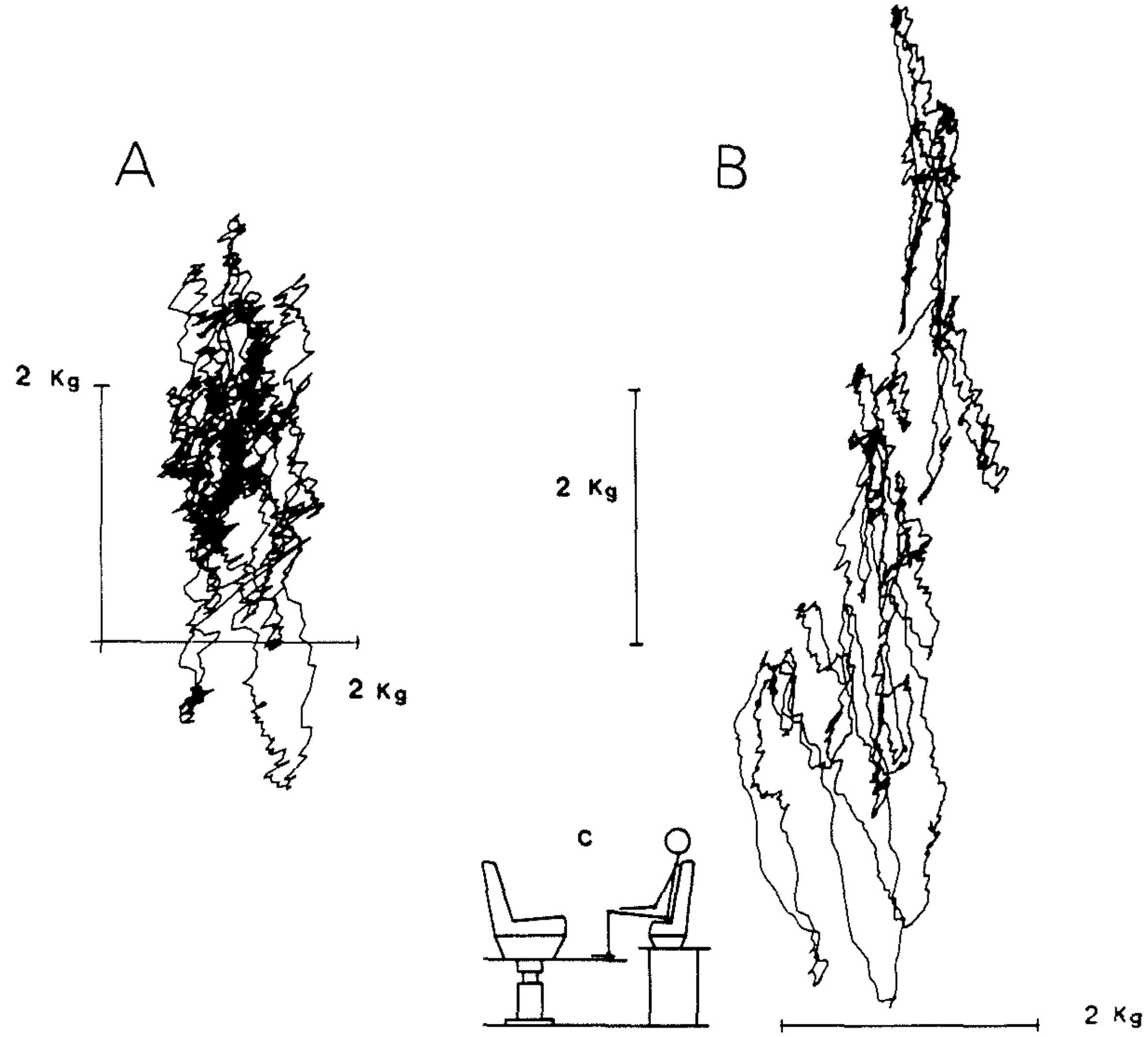

Fig. 3 - Pre- and post-vibration posturograms.
The alterations induced by vibrations were evaluated by 30 second X-Y recordings of lateral (horizontal deflection) and anteroposterior (vertical) components of postural forces. After 30 minutes of vibration (B) applied to the legs (situation illustrated by drawing), there was more than a twofold increase in the overall lateral and anteroposterior force component excursions as compare to pre-vibration ones (A).

velocity signals were altered by varying the maximum amplitude of postural forces. Examination of Fig. 3 indicates a more than twofold increase in the force oscillation amplitude (3Kg to 8Kg) (and corresponding velocity in both directions). Mean values of amplitude histogram descriptive characteristics were utilized to quantify the effects produced in both postural (vertical) force variation and corresponding velocity. The histograms medians (M_X and M_Y) are representative of the S's average standing position as measured by postural X and Y vertical forces during the 30 second trial. The semi-interquartile (SI) is an evaluation index of the postural force mean variation amplitude. All Ss showed a marked enlargement of vertical force amplitude histograms in both directions. However, all Ss did not shift their mean resting position in the same direction. Six of them significantly shifted mean standing position forward and four backward. No systematic relationship was observed between antero-posterior and lateral shifts or between shift direction and S's sensorimotor lateralization.

Head-Trunk and Head Vibrations yielded surprising results in that they did not induce significant alteration of postural mechanisms. Only two Ss showed deviation from control tests. Similarly, no deviation from reference tests was noticed after control trials in which the S was seated for 30 minutes in the noise and air-borne vibration environment that is with all equipments operating, including the hydraulic pump but with no vibration applied.

Tests of significance were systematically applied to the data gathered from all the Ss in the four tested situations. The results showed that WBV and LV situations induced, in all Ss, highly significant disturbances in postural control mechanisms while HTV and HV did not. Fig. 4 summarizes the results obtained in the post-vibration experiments.

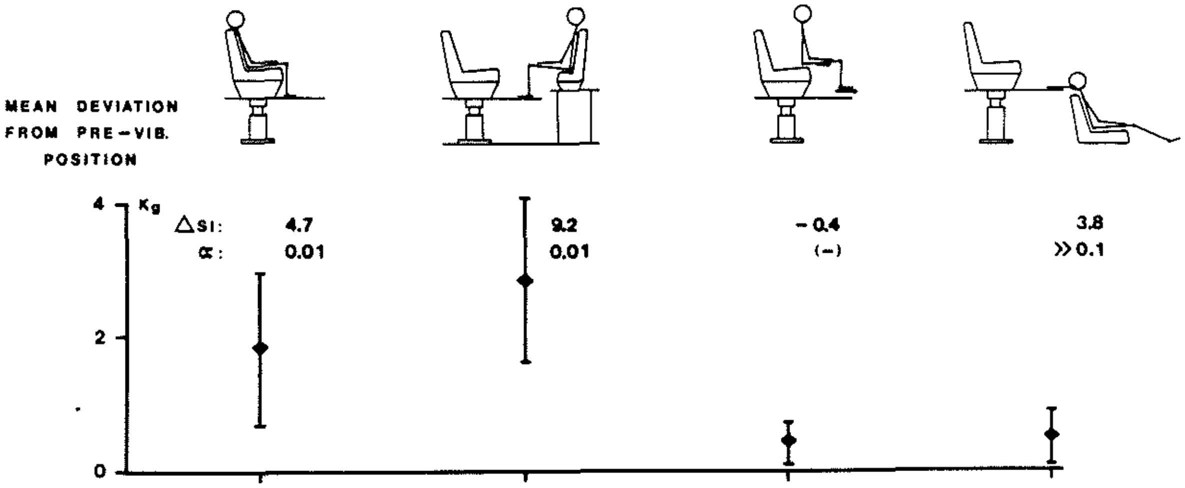

Fig. 4 - Mean postural equilibrium alterations in the situations illustrated by the drawing.

WBV and LV induced, on average, a significant shift of resting position and an increase of oscillation amplitude (Δ SI) while situations HTV and HV had no effect. This suggests that the main site of action of vibration is located in the legs.

For each S, a mean deviation value was determined as the average over 6 trials of the difference between mean resting position before vibration and mean resting position after vibration. The graph represents the average in absolute value ($\propto$) and confidence interval (Z = 0.05) of the mean deviation values obtained from the 10 tested Ss. Likewise, Δ SI is the average of individual differences between pre and post-vibration semi-interquartiles and α is the corresponding probability threshold.

The drawings picture the experimental situations. As can be readily seen, WBV and LV induced,on the average, a significant shift of resting position and an increase of oscillation amplitude (Δ SI) while situations HTV and HV had no effect. This suggests that the main site of action of vibration is located in the legs.

Per-vibration motor effects : Visual examination and computer analysis of stabilometer signals recorded during vibration of standing Ss showed that immediately after the beginning of vibration, the main posture position shifted forward and remained in that new operating location until stimulus cessation. This is shown in Fig. 5. Concomitantly to the mean posture shift, equilibrium oscillation amplitude increased by two to threefold. In some Ss, this increase persisted minutes after vibration

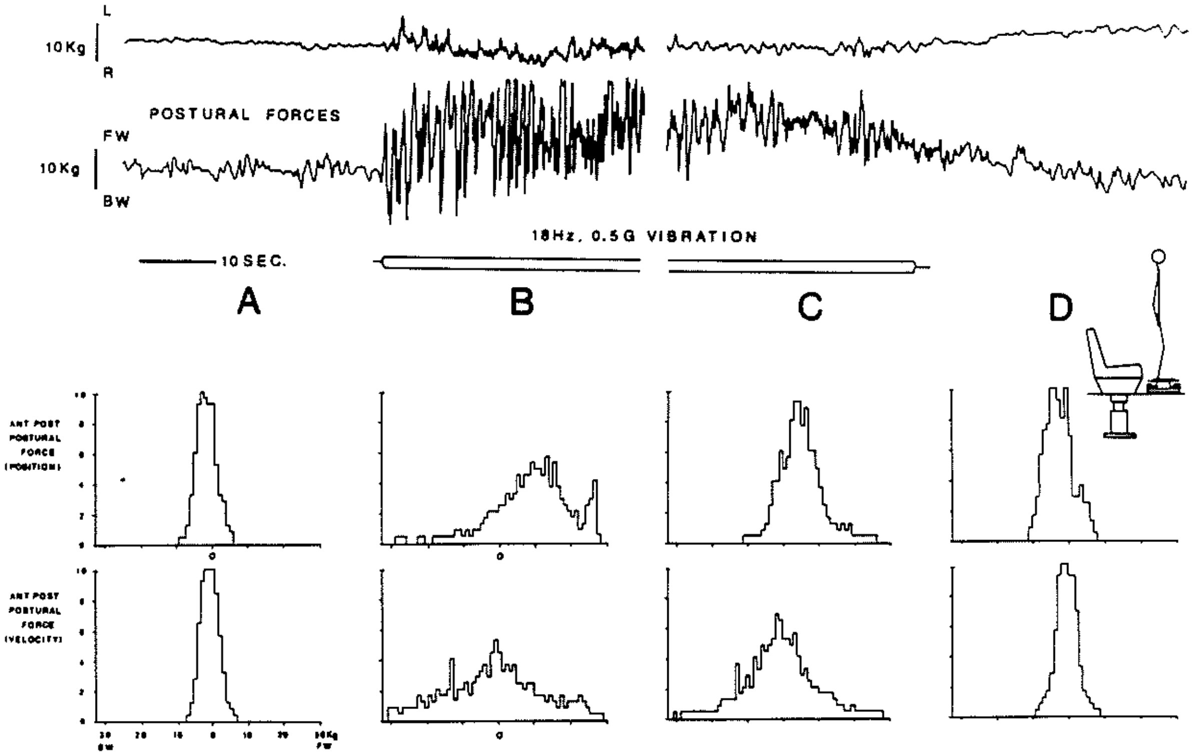

Fig. 5 - Per-vibration effects in standing man.

Stabilometer signals were recorded during vibration applie to a standing S (drawing). Immediately after stimulus application (B) the equilibrium oscillation amplitude increased markedly in bot directions. After 3 min. vibration (C), posture was still altered compared to pre-(A) and post-(D) vibration periods. The lower histo grams , derived from anteroposterior force and its rate of change, were used to characterize the observed effects.Per-vibration histograms were significantly broader, demonstrating an increase of both oscillation amplitude and velocity.

cessation. Position and velocity histograms derived from 15 second recording intervals before, after and at the beginning and end of the vibration period are also shown in Fig. 5 to demonstrate and quantify (threefold semi-interquatile increase) the extent of posture equilibrium alterations under vibration. During vibration, Ss were not aware of the posture mean position shift and the increase of oscillation amplitude. On the contrary, they reported feeling perfectly stable and experiencing a sensation of postural comfort similar to that described above after 30 minute vibrations. In some instances, this phenomenon persisted one to two minutes after stimulus cessation.

Vibration was also demonstrated to markedly alter voluntary controlled postural adjustments. In most trials, the amplitude-defined postural sways were reproduced during vibration with a 25 to 50 percent amplitude increase and a lowering of body sway displacement velocity. In two Ss, the forward sway was so much larger than pre-vibration reference that assistance was provided to prevent falling.

2. Movement and force control study.

Position and velocity control : vibration applied to a S performing to a visual tracking task resulted in a significant alteration in performance. Fig. 6 shows the results obtained in foot and arm tracking as described in the method section (Fig. 2). The pursuit precision was altered both in position and velocity as shown by the direct comparison of target and tracking signals recorded before (left) and during vibration (midle). The effects of vibration outlasted the duration of the stimulus (right). Position and velocity error histograms were used to quantify the effects. Fig. 6 shows position error histograms. They were computed as a position error average between target and S during flexion (blank) and extension (hatched) half cycles. Histograms spreads are significantly larger during and after as compared to before vibration. The observed effects were quivalent for both movement directions and the error in percent was essentially the same in arm and foot tracking tasks. Velocity error histograms also showed that tracking velocity control was altered during and after vibration.

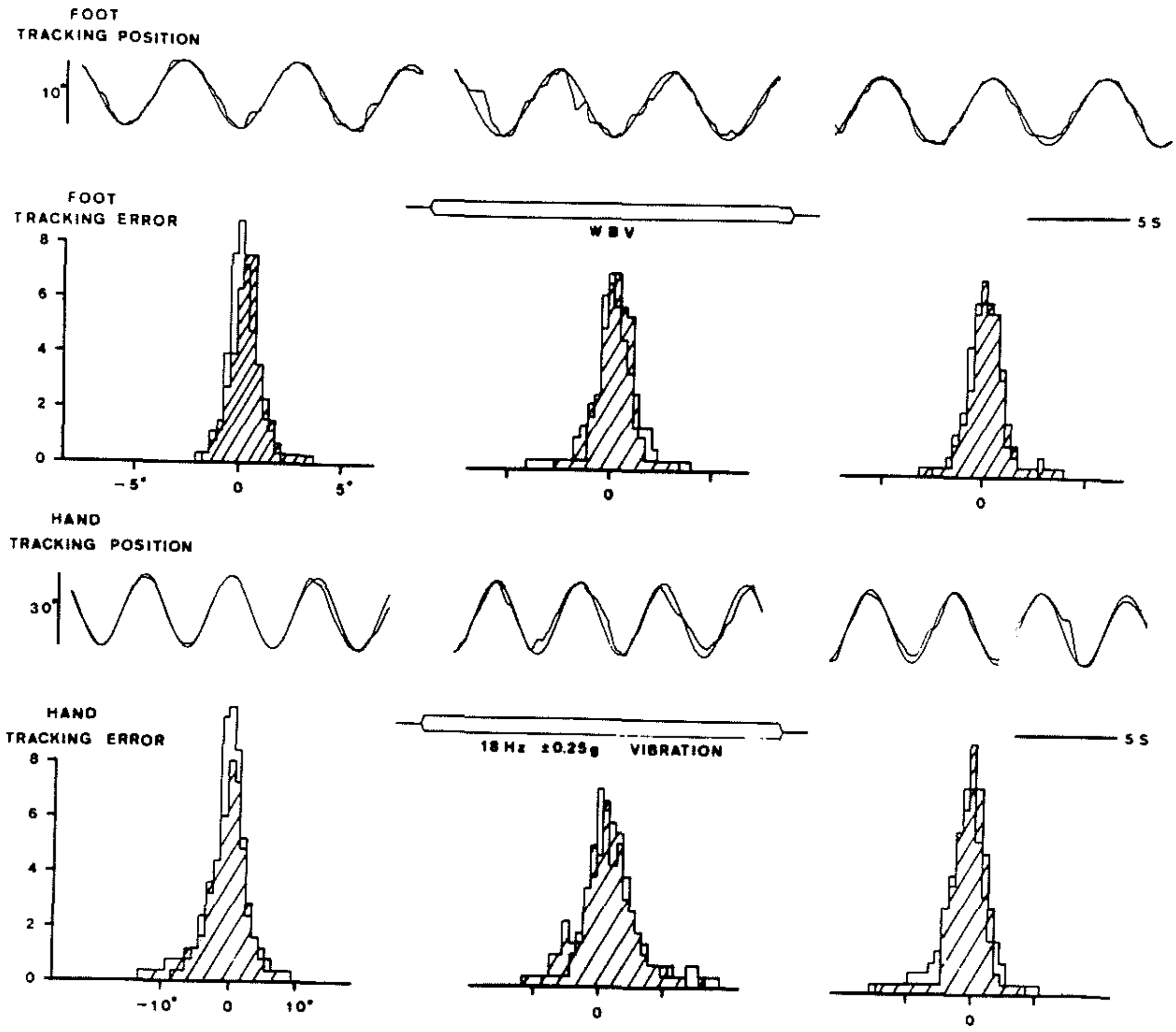

Fig. 6 - Effects of whole-body vibration on visual tracking performance.

Vibration resulted in increase of foot (upper) or hand (lower) tracking error. The alterations outlasted vibration duration. The position error histograms quantify the effects.

Force control : a number of tasks were designed to determine the effects of vibration on force control. Theses tasks effectively demonstrated that both static (maintain) and dynamic (force change rate) force controls were greatly affected. The effects of vibration on combined static-dynamic control are illustrated in Fig. 7. The Ss were required to repetitively produce, with the foot, constant amplitude force steps and maintain the force constant for 2 to 3 **seconds at each step**. When the performance was stabilized, ± 0.25g vibrations were applied to the platform supporting both the seated S and the pedal. Soleus muscle electromyograms (EMGs), integrated EMGs, and force signals are shown in A for two force levels. Vibration is seen to alter both force amplitude and stability control. Depending upon the required force level, step maximum amplitude and force stability increased by 10 to 50 percent. The observed effects outlasted the duration of vibration especially at higher force levels. The graph shown in B illustrates the results obtained from 4 Ss. Each reading is the cumulated average of 25 steps produced by each of the 4 tested Ss before (a), during (b) and after (c) vibration. Three levels of force were examined. They corresponded to torques of 12, 18 and 24 Nm as measured at pedal level.

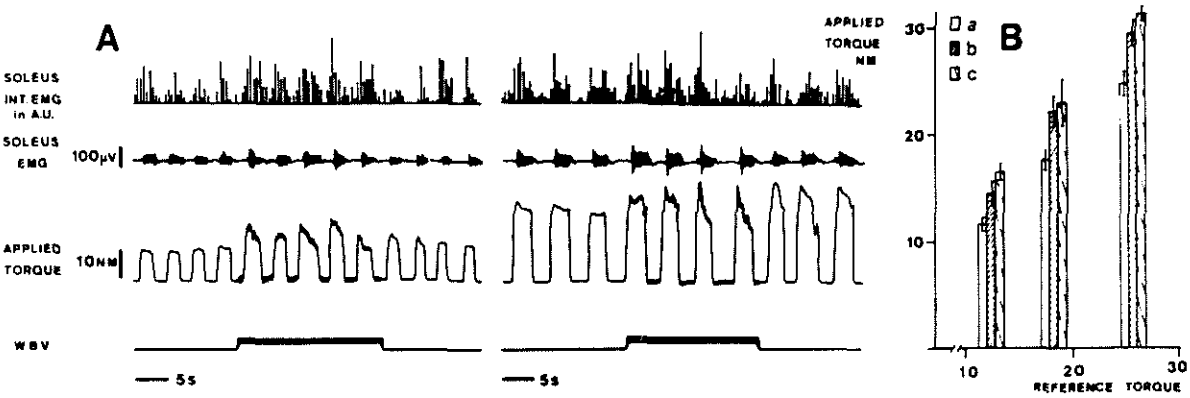

Fig. 7 - Effects of whole-body vibration on force control in stepping task.
Vibration resulted in a significant increase of step force level and decrease of step stability.

IV - DISCUSSION

Previous studies have shown that vibrations applied to muscles or tendons affect movement control (Berthoz, 1971; Hornick, 1973; Roll et al., 1976; Jex and Magdaleno, 1978), and movement perception (Eklund, 1972; Goodwin et al., 1972; Roll et al., 1980).

Our investigation demonstrated conclusively that per- and post-vibration postural equilibrium and force and movement control were significantly altered. Vibration amplitude and stimulation duration were selected to simulate the vibrations encountered in cruising, average-size passenger helicopters.

As mentioned, during vibration and after 30 minute vibration periods, Ss were not aware of the mean posture position shift and increase of postural oscillation amplitude. On the contrary, Ss felt perfectly stable (postural comfort). However, in force and movement control tasks, Ss reported some difficulty in performing the task. The increase of force amplitude and the decrease of force step stability were not perceived. One interpretation of this phenomenon may be proposed. Receptor sensitivity to vibration is such that a powerful afferent flow reaches higher centers and leads to a saturation of movement sensation detectors which is in turn interpreted as an absence of force and position variations.

The comparison of the various amplitude histograms derived from posture vertical forces and related posturograms in the four experimental situations showed that long term vibrations produced large alterations of posture control and regulation mechanisms, and that the vibration site of action was likely to be located in the legs. Indeed, WBV and LV yielded significant changes in equilibrium descriptive characteristics while HTV and HV produced no detectable alteration. The observation that HTV and HV did not induce post-effects suggests that vestibular organs and vestibulospinal systems are either unaffected by high frequency vibrations or that those structures do not habituate and therefore do not exhibit post-effects. The first interpretation is more likely to be valid. The vestibular system frequency responses measured at oculomotor level decrease rapidly beyond 8 Hz (Young, 1969) and therefore should not detect and process solid-transmitted high frequency vibrations. If a 30 minute vibration period were to induce vestibulospinal system habituation, one may expect posture to be affected after stimulus cessation unless lower systems (stretch and joint receptors) compensate for the déficit. This is to be ruled out since HTV induced no effect while LV produced definite alterations. The fact that two Ss showed a slight deviation from control readings after HV may be interpreted as resulting from an effect induced by a spread of the stimulus to neck muscles. Indeed, Gregoric et al.(1978) have shown that high frequency neck muscle vibrations induced forward displacement of S's resting position.

Thus, it appears that vibrations affect sensorimotor system responsible for the maintenance of postural equilibrium and that function alterations last beyond the duration of the stimulus. Óne may tentatively propose that, except for some minor blood flow related problems, motoneurone and muscle fiber functions are basically unaffected. It follows that sensory mechanisms are likely to be responsible for the observed alterations. Among the sensors participating in postural regulation, muscle spindles and more particularly the primary endings are most sensitive to vibrations. This statement is supported by a large body of data on human and non-human Ss (Burke et al., 1976).

How can one account the decrease of postural, force and movement controls during vibration ? In tasks which do not require voluntary control such as posture, a central program is assisted by the servo-controlled myotatic loop. The lower loop gain may also be set by the (postural) program. The latter is automatically (unconsciously) and constantly modified by afferent information from vestibular, muscular and cutaneous signals. During vibration, the "posture center" is invaded by an intense and irrelevent input, primarily from Ia afferences and to a lesser extent from secondary endings, Golgi tendon organs (Burke et al., 1976) and joint receptors (Millar, 1973).

In addition local vibrations have been shown to deeply depress monosynaptic reflex (Homma et al., 1971) and produce presynaptic inhibition at the spinal level (Delwaide et Bonnet, 1969; Desmedt and Godaux, 1978). Both effects may sum to further alter the execution of the postural program and lead to unavoidable larger oscillations around the reference operating point. In fact the lowering of the myotatic negative feedback loop alone will result in an increase of oscillation amplitude.

When voluntary movements of learnt amplitude were to be reproduced during vibration (either from an internal image of the task or by direct visually tracking) readings larger than control ones were observed. A compiled program for voluntary motion likely contains both the muscle activation signals and a feedforward setting of the lower loop gain. As opposed to what was observed with automatic program execution in which vibration resulted in final common pathway gain decrease, voluntary movement programs may counteract the effect induced at spinal level. In that instance, vibration-induced afferences may combine with the command signal and be executed, resulting in movements larger than expected. One may also argue that if the lower loop gain is decreased as a result of vibration, any voluntary activation of the muscle-assumed to be adequately executed- will not be opposed by a sufficient stretch-induced force in the antagonistic muscles. A movement larger or shorter than normal will then develop. Experiments examining spinal monosynaptic reflexes tend to confirm this view since both electrically and mechanically induced tendon jerks are abolished during whole-body vibration and the effects outlast the duration of the stimulus. Fig. 8 illustrates these results. Tendon reflexes are decreased by 70% during 0.25g vibration of the platform supporting the resting seated S.

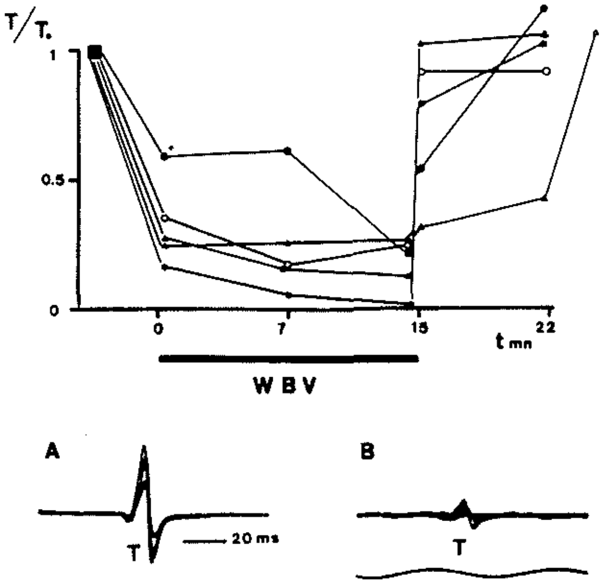

Fig. 8 - Effects of vibration on T-reflex.
WBV was seen to significantly depress T-reflex as illustrated by its change as a function of time for 5 Ss and by superposed individual EMG responses recorded before (A) and during vibration (B). The reflex inhibition persisted after stimulus offset.

V - CONCLUSION

This study demonstrated conclusively that vibration greatly affects human performance by altering postural and movement control mechanisms. Selective application of the vibration to various body parts allowed us to show that the muscular proprioception system is primarily affected while the vestibular system does not seem to be a major vibration target.

As suggested by the relevent literature, vibration particularly affects muscular proprioceptors whose role is essential in the generation of movement regulation and movement control signals. These observations suggest that particular care should be taken in helicopters and other vibrating vehicules to prevent vibration from reaching muscular masses, especially those involved in motor tasks requiring position, velocity and force controls.

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