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General Features of Vibration-Induced Effects on Balance

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ABSTRACT

Tests on healthy adults and patients showed that vibration of certain leg and trunk muscles caused involuntary inclination movements. These vibration-induced falling reactions (VIFs) were recorded by letting the subjects stand on a force platform signalling changes in the body inclination. The equilibration contractions in the leg muscles during voluntary counteraction of such falling were shown by the irregular oscillations also included in the signal, which could be separated from the slower sway signals. The amount of these oscillations in the supportive forces served to indicate the unsteadiness produced by vibration. Analysis of how various factors influenced the strength of the postural reactions, VIF-latency measurements and studies of VIF-responses in certain patients lend support to the following conclusions. 1) Certain leg and trunk muscles are particularly important as afferent sources for equilibrium during standing. 2) Vibration-induced afferent inflow from these muscles tends to bring the body out of balance, not because of local changes of tension in the muscles stimulated (segmental reflex effects) but because of widespread postural adjustments from supraspinal structures. 3) The muscle end organs mainly responsible for the reactions described are probably the secondary spindle endings.

INTRODUCTION

Muscle vibration has proved to be an efficient stimulus for human intramuscular stretch receptors (13) and in many previous studies this stimulation technique has been used to investigate how sustained activity in muscle afferents can affect muscle tonus and motor control (e.g. 8, reviews: 10, 11). In these studies the vibratory stimulus was applied to muscles not engaged in supporting the body or maintaining the equilibrium. Under such conditions the vibration-induced tonus shifts are normally restricted to the muscles stimulated and to their antagonists and on the whole, the motor effects are explicable in terms of segmental reflex phenomena. This holds true not only for the tonic vibration reflex (TVR) which probably originates from primary spindle endings exerting an autogenetic excitatory and a reciprocal inhibitory effect (e.g. 12) but also for the autogenetic inhibitory effects that may appear in response to a low frequency vibration of high amplitude (7) and that presumably arise from secondary spindle endings or Golgi tendon organs.

However, the different groups of muscle afferents have not only spinal projections to the motoneurons, they also project to various supraspinal structures involved in motor control. In particular the supraspinal structures involved in the regulation of body posture and equilibrium during standing are generally believed to be dependent on accurate information from somatic proprioception for their proper functioning (18) but the relative importance of the various possible receptor populations is unknown. On these grounds it was considered that previous studies of vibration reflexes should be complemented with investigations of how posture and equilibrium during standing can be affected by bilaterally applied vibratory stimulation to various leg and trunk muscles.

Much work has previously been done to explore the mechanical and neurophysiological mechanisms involved in the act of standing. EMG-recordings from leg and trunk muscles (e.g. 15, 16, 23, 24), sway measurements (e.g. 4, cf. 9) and analysis of force signals from standing platforms (e.g. 25, 26) have provided a great deal of data as to how various muscles operate, how various body segments sway in relation to each other and how the body as a whole sways around the ankle joints, all the time keeping the plumbline from the common centre of gravity projected close to the centre of the area of support. The signal from a force platform gauging the antero-posterior distribution of the supportive forces has been chosen for the present recording of standing. The main reason for this is that it contains both a reflection of the inclination of the body in relation to the base and, in addition, the superimposed faster oscillations probably reflecting dynamic equilibration contractions (DECs henceforth) (cf. 22). The latter have been shown to give a more sensitive indication of the demand on the central structures regulating balance than do the conventional sway measurements (9).

The present report is primarily intended as a description of how the body reacts during ordinary standing when bilateral mechanical vibration is applied to certain muscle groups in the trunk and the lower extremities. It will be shown that the stimulus tends to induce a rotation of the whole body over the ankle joints and this basic phenomenon is abbreviated to VIF, i.e. vibration-induced falling. The results indicate that such a VIF is an automatic reaction of the centres of equilibrium in response to the vibration-induced change in the postural information coming from the vibrated muscles. During voluntary counteraction of the VIF there is no visible change in the inclination of the body but instead the DECs increase. In the following, the abbreviation VIF not only denotes the change in the inclination of the body it also connotes the central reflex adjustments. Some of the findings have been preliminarily reported (5).

METHODS

Abbreviations

VIF and DEC were explained above. SOL, TA and HAM are in the following used as abbreviations to denote the calf muscle groups, the anterior tibial muscle groups and the hamstrings respectively. Similarly, VSOL is used to abbreviate the expression "vibration of the calf muscle groups". M and T are prefixes for the site of the application of the stimulus to muscle and tendon respectively; thus M-VTA means vibration with a muscular application over the anterior tibial muscle groups. CCG stands for the common centre of gravity of the body.

Screening tests

The basic phenomenon, i.e. the VIF, has been observed by mere inspection in over one hundred normal subjects and also in a large group of patients with various motor disorders. In these screening procedures T-VSOL was the most common test (additional details are given below) and the vibrators were manually activated by means of switches. After having observed the response to the stimulus, the subjects were asked to remain in the original position during a second vibration period. Thus, they voluntarily counteracted the VIF. The body movements during this procedure were observed as was the reaction at the sudden stop of vibration. In some of the subjects the vibrators were then moved to other muscle groups as described below and the procedure repeated.

Recording of VIF during passivity

The author has been the most commonly used subject for obtaining the results illustrated. The essence of the findings in normal man has been recorded in colleagues or other members of the laboratory staff. They included men and women from 20 to 45 years of age, all without any overt signs of neurological symptoms or a history thereof. The subjects stood on a *force platform* measuring 35 × 35 cm (9). It was required that the position should be symmetrical and that arm, hip and knee movements should be avoided. The *instructions* included keeping the heels close together but not in contact; the angle of the feet was optional. Shoes were not usually worn during the tests. Tendencies to stand at attention or to droop were corrected by instruction. Some subjects reacted very actively in response to the start of vibration in that they rapidly and with obvious muscle contractions counteracted any deviation from the original position. Such persons were reassured and asked "to let the body automatically handle its balance". Thus, the subjects were *passive* in the sense that they did not of own volition interfere with the reactions produced by the stimulus.

Two identical *vibrators* (6) were used simultaneously; they were each fastened right across a muscle or its distal tendon by means of sturdy rubber bands over corresponding sites, e.g. over the muscle belly of each calf, i.e. M-VSOL, see Fig. 3. During vibration of trunk muscles an elastic roller kept the vibrators in contact with the underlying tissues. The vibrators were operated by an electric clock which switched the power on during a pre-selected time, usually 1–2 s. The interval between two vibration periods could also be preset and was generally 6–10 s. The vibration amplitude could be chosen by the use of different eccentrics, it was largely independent of the frequency which was continuously variable between about 20–165 Hz.

The signal from the force transducer in the standing platform could be recorded directly by an *inkwriter* (Elema Mingograph) or stored on *tape* for which a PI 6200 was used. In the first case, it was simultaneously fed to a *computer* of average transients (CAT 1000) the sweep of which was started by the clock (see Fig. 1 A). Six such sweeps were generally used to obtain a mean value of the VIFs. Besides providing a mean value, the procedure reduced the persistent, irregular dynamic force components (DECs) also contained in the signal. The same analysing procedure could be made when the signals were recorded on tape. The duration of the sweep in an averaged VIF-record is generally 4.1 s. A backward body sway causes an upward deflection in all the recordings shown (cf. the single VIF-recordings in relation to the foot-print in Fig. 4). At the start and/or stop of vibration there are often small spikes in force traces which are artefacts from the action of the relays in the clock.

Recording of DECs

This analysing procedure has been separately described (9). In brief it consists of separation (by sub-sonic filters) and measurement (by an integrator) of certain force components which more closely than conventional sway measurements reflect the output (amount of DECs) from the central nervous structures regulating posture. The signal from the force platform was thus fed to a special analyser and the tests also differed from the sway experiments in that the vibration periods were much longer, usually up to one minute. In addition, the instructions included the subject *counteracting* the tendency to sway and remaining in the original position. Otherwise, the experimental conditions corresponded to those described above.

Calibration of sway

The force signal was calibrated by applying 10 kg 15 cm from the axis of the platform. This gave a signal of 15 Nm (Newtonmeter, 1 Nm = 0.738 lbf ·f) which corresponds to a change of about 1.2° in the inclination of the body in a subject weighing 75–80 kg. These figures are further elucidated in the next paragraph, where the values apply to the author (185 cm, 78 kg).

A VIF is primarily a change in the inclination of the body and it is natural to measure it in degrees (angle). On the other hand, the procedure used—measurement of changes in the supportive forces—demands the use of Nm. With slow movements such as VIF, the force signal and the inclination of the body change in parallel. Measurement and calculations indicated that the dynamic exaggeration of the force signal is below 8 per cent during voluntary swaying with a time period corresponding to that of a VIF, i.e. about 8 s. The position of the CCG (although the weight of the feet should in fact not be included since these are not moved) is about 56% of the body height (3) measured from the ground (= 104 cm). With allowance for the feet about $9.81 \times (78-2 \times 0.8) =$ 750 N can be said to be concentrated at the CCG. The vertical projection from the CCG stays close to the geometric centre of the supporting base. Slow voluntary swaying in the sagittal plane is a matter of controlling the CCG-position so that it stays over the supporting base, the antero-posterior extent of which is about 20 cm (the toes are not included, they carry no weight, cf. 21). Thus, a slow maximal sway may in theory amount to $750 \times 0.20 = 150$ Nm. The transverse joint axes of the ankles are about 9 cm above the ground; it can be calculated that in the original position spontaneously adopted (CCG vertically over the centre of the base) there is a 3° forward inclination of the line from the CCG to the axis of rotation. It can be estimated that the range of this angle is in theory from about 9° to −3° (CCG behind the axis in the latter case). Hence, the maximum range of sway is about 12° or 150 Nm as stated above. Thus, a change of 12.5 Nm in the supportive forces corresponds to a sway of 1°. Note that this is only valid for the specified body weight and for slow body movements. Man's erect posture is to a large extent a mechanical affair (cf. 14, 28). Tonic muscle activity is present mainly in the calf muscles, the ilio-psoas muscles and along the spine. Postural corrections seem to be executed partly by means of short-lasting contractions, e.g. in TA which generally is not contracting during standing. For further aspects and details see e.g. 1, 3, 9, 14, 18, 20, 26, 27.

RESULTS

GENERAL OBSERVATIONS IN NORMAL SUBJECTS

(a) Vibration-induced falling (VIF) elicitable from various muscle groups.

Most tests without registration were performed with T-VSOL, 1.8 mm, 150 Hz and closed eyes. All subjects responded to this vibratory stimulus of the Achilles' tendons with a *backward* sway of the body round the ankle joints. The response was often so strong that the subject had to take a step backward to avoid falling. Once aware of this postural effect all subjects could counteract it and remain in the original position during continued vibration. This voluntary counteraction, however, was accompanied by an increased leg muscle activity of dynamic character indicating a certain "unsteadiness", and a sudden stop of the vibrators elicited a distinct sway in the direction opposite to that of the VIF.

In about 20 subjects the vibrators were systematically moved from one muscle group to another to find out from which other sites VIF-reactions could be produced. The results were quite consistent in that they showed that vibration of the quadriceps muscle groups and of the abdominal muscles was largely ineffective whereas VIFs directed *forward* could be produced by vibrating TA, HAM and the lumbar and the thoracic parts of the erectores spinae. Besides being of opposite direction, these VIFs had similar characteristics to those produced by VSOL.

When the stimulus had a duration of over 2 to 3 s it was usually impossible for the subject to remain passive during the test. To prevent falling he had either to move his feet or to try leaning in a direction opposite to the VIF. With a short stimulus duration of about 1 s such compensations could be avoided, for such stimuli were usually not sufficient to cause sways that passed the limit of possible inclination. Stimuli of this type caused a relatively smooth body movement, a rotation of the body about the ankle joints resembling half a cycle of a voluntary sway in the sagittal plane.

(*b*) *EMG-observations*

It is well-known that the CCG projects vertically in front of the ankle joints during ordinary standing and that this is accompanied by a contraction in the calf muscles to prevent forward falling (16, 23). The contraction is graded in relation to the body inclination and ceases if the plumb line from the CCG passes behind the joint axes. The patterns of activity in EMG-recordings from various muscles in the lower limbs were investigated in some normal subjects using conventional surface electrodes. It was not possible to detect any significant alteration in activity during VIFs elicited from various muscle groups as compared to the activity during voluntary swaying. Thus, the sway backwards during VSOL was accompanied by a gradual cessation of the preexisting activity in the calf muscles and a concurrent activation of the anterior tibial muscles. However, at the sudden start of VSOL, there was often an initial burst of activity, followed by a silent period in the calf muscles. Sometimes a diminishing clonic activity was observed in such recordings.

(*c*) *Sensations during VIF*

This account was compiled from introspection and from interviewing several subjects. It was apparent that VSOL and VTA are different from VHAM and vibration of the erectores spinae especially regarding what is felt during voluntary counteraction. All subjects had great difficulty in defining what they counteracted during VSOL and VTA. Similarly, a VIF in response to VSOL and VTA "just happened" without any obvious perception of how the movement was induced. This contrasted sharply to the perceptual events during VHAM and vibration of the erectores spinae. These stimuli induced a strong sensation of a "force" very similar to a continuous push from behind applied to the vibrators. It was especially apparent during counteraction and disappeared completely when the limbs were not engaged in maintaining the standing position. Thus, these force sensations are only related to the act of standing and appear in addition to the ordinary awareness of the vibration as such. The strength of the sensation during counteraction seemed to parallel the effectiveness of the postural stimulus. A frequency increase, for instance, was accompanied by a stronger sensation.

FORCE PLATFORM TESTS IN NORMAL SUBJECTS

(*a*) *Examples of typical signals in platform tests*

Fig. 1 shows most of the various signals and events as they appeared during a VIF-experiment (A and B) and also the computed records available afterwards (C). In Fig. 1 A and B are shown the greatest and smallest sway responses to VSOL and VTA respectively, partly to indicate the maximum range of variability. The single VIFs were usually the same size but could occasionally be markedly greater or smaller. The latter was mainly noted when there were obvious signs that the subject did not remain passive and it did not occur in any systematic pattern. The signals marked 3 and 4 in Fig. 1 show primarily the body inclination but also that shortlasting forces such as a "tendon jerk" can occur in force records (3) without affecting notably the goniometer record. It can also be seen that the DECs are more prominent in Fig. 1 B than in 1 A, which is also seen in the filtered and integrated signals (2).

1. *Non-sway forces in VIF-records.* The main deviation in VIF-records which represents the body movement is generally preceded by a small deflection of the opposite direction. The phasic stretch reflex at the sudden start of the vibrators is clearly an apparent cause of such deflections in VSOL-experiments (Fig. 1 C). For other muscle groups it is conceivable that the first impacts of the vibrators can somehow contribute to this force component. Small movements within the body, especially at the knee joints can at times probably account for artefacts of this sort. However, such short-lasting forces do not cause any visible swaying movements. Bilaterally applied single electric shocks to leg nerves produced similar initial force components but did not cause any ensuing body movement resembling a VIF. When measuring the amplitude of a VIF, such deviations have been excluded by using the very first part of the record as initial position such as indicated in Fig. 1 C. A corresponding force artefact is generally present at "off" after a prolonged vibration, which can be seen in Fig. 5 B. Similarly, the small notches in subjects 2 and 3 in Fig. 4 indicate that these less well-trained subjects probably exerted a slight, unconscious counteraction.

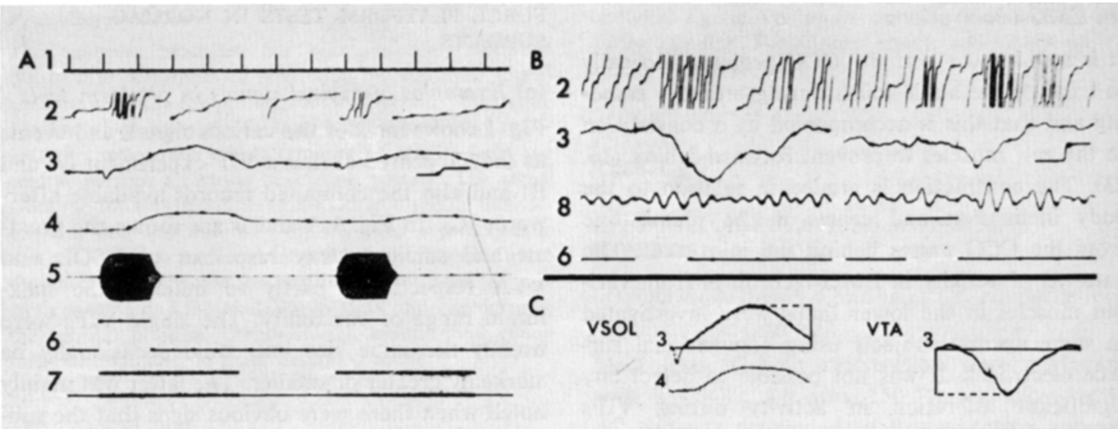

Fig. 1. To illustrate typical recordings in a trained subject. (A) and (B) are examples of the original signals recorded during the experiments and (C) shows the average VIF-records obtained from the computer afterwards. The largest and smallest VIF of the six are shown in (A) and (B). (A) VSOL, 1.4 mm, 120 Hz, open eyes. (B) VTA, 1.4 mm 65 Hz, eyes closed. Note DECs and increase in the number of 2 Hz-integrations. In (A) the "tendon jerks" and not the VIF are responsible for the two groups of integrations which are somewhat delayed due to transients in filter action. *Numerals: 1,* time, 1 pulse/s; *2,* 2 Hz-integrator signal; *3,* signal from transducer in standing platform, small insertions are calibrations corresponding to a 15 Nm backward sway; *4,* body inclination (angle between platform and leg); *5,* the stimulus, i.e. the acceleration of the load-end of one of the vibrators; *6,* signal from the clock used to operate vibrators (start and stop) and computer (start); *7,* computer's sweep; *8,* output from 2 Hz-filter. (C) the average VIF-records with indication of initial position as used for amplitude measurement. During the VSOL-experiment both channels 3 and 4 were fed to the computer. The angle starts to alter after about 0.7 s, the initial "tendon jerks" do not appear in channel 4. The amplitudes of the computed force signals are about 45 Nm which corresponds to a sway of about 3.5°. Time as in (A) and (B).

2. *Knee joint stability.* The spontaneous response to VHAM in many unprepared subjects was a flexion of the knees (Fig. 2). The subject merely lowered himself without any change in the inclination of the body. The response is abrupt and has a shorter latency than the VIF, which also can be seen in Fig. 2. One of the first impacts of the vibrators made the mechanical stability of the knee joints give way. This was easily avoided by a slight voluntary hyperextension to secure the knee position. Vibration with a slow frequency increase did not give this effect but it could appear with maximum frequency vibration also with an amplitude too small to induce a VIF (0.7–0.9 mm, see below).

(b) Conformity of the two recording procedures

The two methods used to gauge the VIF responses gave roughly consonant results. Thus, a procedure that increases the amplitude of the VIF is likely to increase the DECs during counteraction. For instance, this applies to the effects of stimulating the muscle bellies and tendons respectively (see Fig. 3 to the right). Another example: the effects of different vibration amplitudes on posture were not measurable with 0.7 or 0.9 mm amplitudes either as a systematic sway (see below) or as an

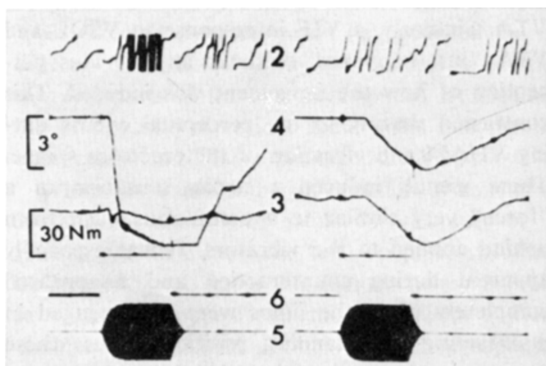

Fig. 2. Illustration of the different VHAM-responses. *Left:* mechanical stability of the knee joints surreptitiously collapses (4) and the unprepared subject merely lowers himself without a change in the inclination (3) of the body. *Right:* adequate VIF, 3 and 4 change in parallel. Note latency difference. Numerals as in Fig. 1. Vibration for 1.5 s.

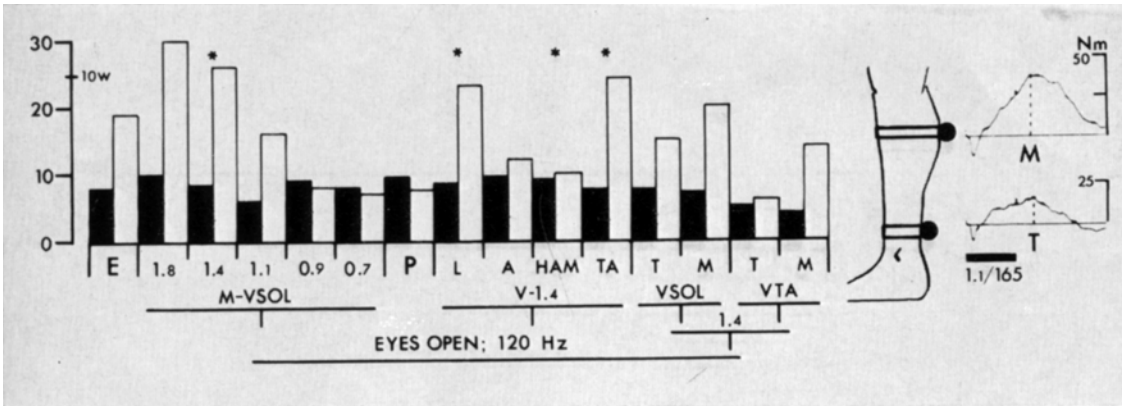

Fig. 3. Left: illustrates the output (DECs) from centres regulating balance during various tests as indicated below. Control periods (black areas) and tests (open areas) had a duration of about 40 s from which a typical 15 s period was measured regarding the amount of DECs in the 2 Hz channel of the analyser (ordinate, 10 W is also indicated). *E*, effect of eye closure; *P*, placebo, was performed with the vibrators hand-held. *L* and *A*, lumbar and abdomen respectively. * indicates tests with the same stimulus parameters applied to different "VIF-muscles" of which HAM was an exception this time. Additional comments in text. *Right:* effect of vibrating the muscle bellies (*M*) and the tendons (*T*) as the sketch shows. Average VIFs in response to VSOL, 1.1 mm, 165 Hz, eyes shut.

increase in the DECs. The latter can be seen to the left in Fig. 3 where the recorded effects of different vibration amplitudes applied to SOL are shown. Conversely, both the DECs and the VIF-magnitudes increased roughly in proportion when vibration of 1.1–1.8 mm was used. In Fig. 3, however, the tests labelled * contain one exception. At this particular occasion VHAM did not cause the increase in integrator output which could have been predicted from the outcome of other tests and in accordance with what had been found at other occasions. Similarly, vibration of the abdominal muscles which usually gives no VIF showed a slight increase in the dynamic forces during prolonged vibration.

(*c*) *Different factors affecting VIF*

1. *Initial position.* The computed VIF-records at the top of Fig. 4 were obtained in three different subjects. There is a clear difference as regards the amplitudes of the responses and the reason for this discrepancy between the subjects lies mostly in the fact that they used different initial positions. The low frequency vibration of the Achilles' tendons (37 Hz) produced a comparatively small VIF but the exact magnitude seemed to depend on the inclination of the body, the response decreasing with increasing forward inclination (subject 1). The foot-print in Fig. 4 was constructed from force measurements in subject 1 but applies largely to the other subjects also. Subject 1 stood close to the ordinary mean posture during the test (the single VIF marked *a* is an example thereof) whereas subjects 2 and 3 leaned forward somewhat more. The additional single VIF-records for subject 1 (*b* and *c*) were obtained afterwards; they are 8 and 0 Nm respectively. The movement (VOL) in the lowest record (*c*) is a voluntary change of position. Thus, it is necessary to consider the original position since, especially with a comparatively weak stimulation, it can strongly affect the outcome of a test.

2. *Prolonged experimentation.* The DEC-experiments shown in Fig. 3 were performed in time order from left to right. The control level (black areas) tends to fluctuate in "slow waves" with, for instance, the smallest values during T/M-VTA at the right. Similar slow variations have also been suspected to occur during time-consuming experiments with measurement of the amplitudes of computed VIFs. Thus, a control initially obtained at such tests may differ slightly from that after the completion of the experiment. The phenomenon has not been more closely studied but it was felt that 8–10 min is a time period during which no major shifts take place.

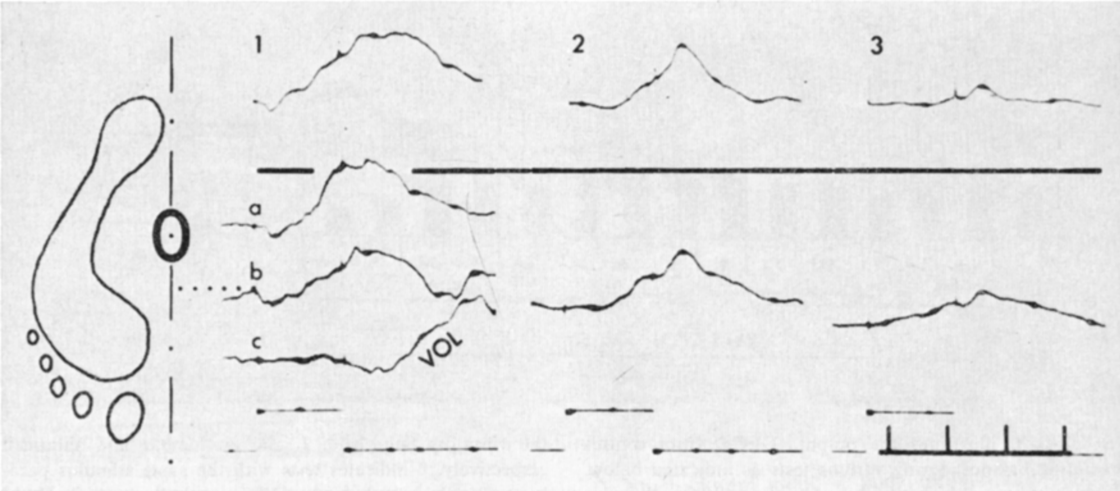

Fig. 4. Illustrates the effect of the initial position during experiments with low vibration frequency. *Upper row:* averaged VIFs in three different subjects, stimulus: M-VSOL, 1.8 mm, 37 Hz, eyes shut. Examples of pertinent single VIF-records (a for subject 1) are shown below the line. Each point on all the single VIFs is related to the foot-print as indicated for the initial position in *b* (· · ·). The symmetry line of the supporting base is indicated as is the area onto which the CCG projects during ordinary standing. VOL indicates a voluntary change of position. Calibration: the foot-print. 1 s markings in lower, right part.

3. *Vibration amplitude.* It was found that a vibration with an amplitude of 0.9 mm and maximal frequency could elicit a small VIF in some subjects particularly in response to M-VSOL. In one typical experiment with T-VSOL, 160 Hz, 1.5 s the following values for VIF-magnitude were obtained at different vibration amplitudes: 65 Nm with 1.8 mm, 38 and 20 Nm with 1.4 and 1.1 mm respectively, 0.9 and 0.7 mm produced initial "tendon jerks" but no VIF. The corresponding relations as measured in the dynamic force components are illustrated to the left in Fig. 3. It can be seen that 0.7 and 0.9 mm vibration amplitude did not affect the DECs and that 1.1, 1.4 and 1.8 mm increased these "unsteadiness oscillations" in proportion.

4. *Vibration frequency.* Fig. 5 A shows examples of the relation between VIF-amplitudes and the stimulus frequency. A higher vibration frequency yields a greater body sway. The increase seems to be linear to judge from the three VSOL-tests. Extrapolation of the values plotted in the diagram shows that the abscissa becomes intersected between 12 and 34 Hz.

In related experiments the subjects performed repeated VSOLs and VTAs themselves, successively reducing the vibration frequency until they could not detect any VIF or its corresponding off-effect. The frequency for a postural effect to appear or disappear was hence found to be in the range of 25–30 Hz. In another experiment 12 members of the laboratory staff were examined using VSOL, 1.8 mm, 40 Hz. It was found that small but distinct VIFs could be elicited in all but one person. In the latter case prolonged stimulation revealed off-effects. It was also found in these tests that the effect of vibration was smoothly graded in relation to the stimulus frequency. Thus, when reducing the vibrator frequency vountary counteraction became correspondingly easier and, similarly, with intermittent stimulation of short duration and successive frequency reduction VIFs became smaller until they could not be detected. In fact, an indication of a step in the input-output relations was never found for stimulus frequency.

5. *Site of stimulus application.* Interpretation of what receptors are involved in producing VIF-reactions may be facilitated by comparing the response to one and the same stimulus applied over the muscle bellies and tendons respectively. Experiments pertaining to these matters can best be

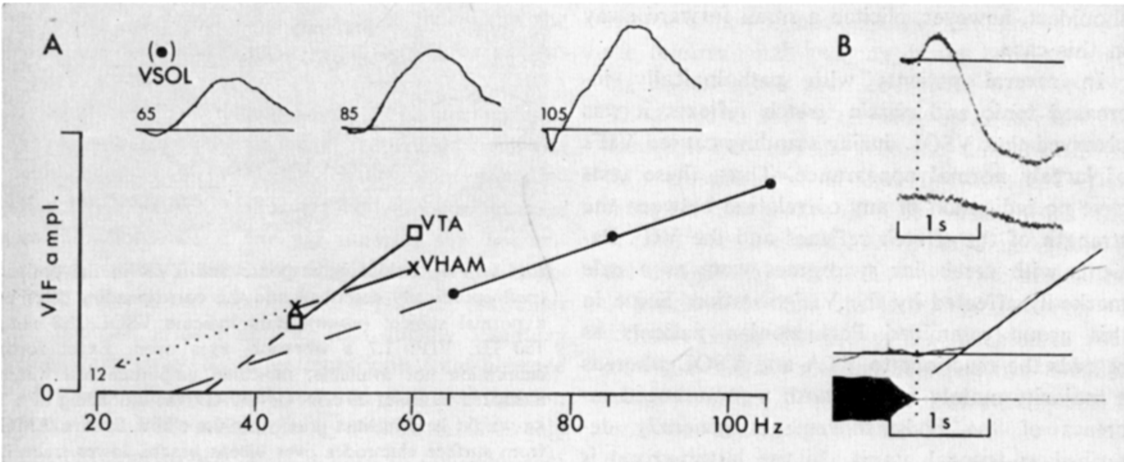

Fig. 5. (A) VIF (average of six) and vibration frequency. *Ordinate:* VIF-amplitude, arbitrary scale. *Abscissa:* vibration frequency, 20–105 Hz. Only VSOL-recordings are illustrated; included are the base-lines for amplitude measurement. M-stimulation, 1.8 mm, 1.6 s also for VHAM and VTA. Hatched and dotted lines are used for extrapolating. (B) Illustrates "off-latency". *Upper:* force and inclination as for VSOL in Fig. 1 *C*. The computer sweep was started by the off-signal from the clock, sweep time 2.05 s. The preceding stimulus was M-VSOL, 1.4 mm, 125 Hz during 8–10 s. *Lower:* force and acceleration towards the end of a corresponding VHAM-stimulation. Dotted lines indicate the moments vibration ceases. Initial position line in both, help-line for off-sway included in the lower record.

performed with VSOL but are also feasible with VTA. The outcome of such experiments is illustrated to the far right in Fig. 3 including the 4 last DEC-tests. It is apparent that vibration of the muscle bellies yields a stronger effect than vibration of the tendons.

(*d*) *Latency of VIF*

It can be seen in Figs. 1 and 2 that the change in the body inclination as reflected by the force signal does not begin until after about half a second. When vibration stopped during counteraction, the latency of the "off-sway" was usually found to be somewhat shorter. Fig. 5 B shows examples of such latency measurements using VSOL and VHAM. With single trials the variability was relatively great, 0.33 s was found to be shortest "latency". As regards the computed off-sways at the top of Fig. 5 B the latency measurement is somewhat complicated due to the force component above the line which indicates the initial position. The force signal crosses that line 0.40 s after vibration has stopped and this figure has been taken as a measure of the latency. It was estimated that the angle signal started to alter 0.54 s after vibration stopped, which should be compared with about 0.7 s in Fig. 1 C. Thus, the sway effect of removing a postural vibratory stimulus becomes demonstrable after about 0.4 s.

FINDINGS IN PATIENTS

(*a*) *General observations*

Over two hundred patients referred to the laboratory for ordinary EMG examination have been tested. VIF-reactions were found in all who could stand by themselves but was modified in different ways depending on the underlying motor disturbance. In patients with parkinsonism, for instance, insufficient protective postural adjustments were undertaken to stop the sway during prolonged stimulation. Thus, these patients had to be supported to prevent them from falling. A VIF could also be absent or extremely small in response to stimulation of certain muscle groups. This was generally seen in cases with extensive denervations. Thus, one patient who had a pronounced Charcot-Marie-Tooth's disease, could stand unsteadily with his eyes open but VSOL, VTA and VHAM had no effect on his balance. Vibration of the trunk muscles between the shoulders, however, elicited a small forward sway in this case.

In several patients with pathologically increased tonic and phasic stretch reflexes it was observed that VSOL during standing caused VIFs of largely normal appearance. Thus, these tests gave no indication of any correlation between the strength of the stretch reflexes and the VIF. Patients with cerebellar syndromes were as a rule markedly affected by the VIF-vibration. Some in this group resembled Parkinsonian patients as regards the reactions to VTA and VSOL whereas a majority mainly reacted with a pronounced increase of the body movements generally described as truncal ataxia. In the latter group it could be hard to detect the direction of the VIF, which was small in relation to the large, exaggerated "compensating" body and arm movements. However, a VIF of inversed direction was never observed.

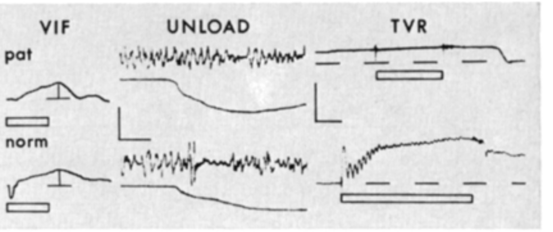

Fig. 6. VIF, unloading response and TVR in the patient (*pat*) specifically described and the corresponding tests in a normal subject (*norm*). Bars indicate VSOL, 1.8 mm, 150 Hz. VIF: 1.7 s vibration, eyes open. Exact force calibration not available; indicated amplitude afterwards estimated to about 20 Nm. UNLOAD, the unloading of a 2 kg weight held against gravity by the elbow flexors. EMG from surface electrodes over biceps brachi, lower trace is elbow angle. Calibration: 25°, 100 ms. The last two spikes before EMG-silence in "norm" are artefacts. Patient's forearm accelerates faster and moves longer than it does in the subject. *TVR:* patient exerts a voluntary plantar flexion to facilitate the motoneuron excitability of the calf muscles. The normal subject is relaxed and passive during the test. Calibration: 10 Nm, 1 s. Zero force is indicated by the interrupted lines.

(*b*) *Force platform tests in patients*

About 15 patients were examined while standing on the force platform. The main symptom of this group was impaired equilibrium although the underlaying cause was uncertain or unknown in many cases. All the patients showed an increase in the amount of the DECs as compared to a normal subject of the corresponding body weight. The signal from the platform could, for example, show a 40-fold increase in the 2 Hz-integrator. Thus, although the VIF can be reduced in patients with equilibrium disturbances the spontaneous DECs only show an increase to judge from this limited group.

The findings in a 22-year-old female with a presumably hereditary neuropathy are important. Her clinical picture resembled that of Friedreich's ataxia. From a neurophysiological point of view, she lacked all signs of reflex effects of known primary spindle afferent origin. Thus, there were no tendon jerks in leg and arm muscles, no tonic vibration reflexes neither during relaxation nor during slight or moderate volitional contractions. She lacked the abrupt cessation of EMG-activity in response to a sudden unloading of a voluntary contraction, cf. a pathological rebound test of Gordon Holmes. Her movements were accompanied by a moderate ataxia. EMG showed slight denervation in the short toe extensors and motor conduction velocity was about 30 m/s in arm and leg nerves. Fig. 6 shows the VIF of this patient with VSOL, 1.8 mm, 150 Hz. The same vibrator parameters were used to vibrate the Achilles' tendon during a voluntary, nonpostural contraction. Fig. 6 also shows the response to a sudden unloading of a 2 kg weight held against gravity by the elbow flexors. For comparison the same procedures in a normal subject are included. There is no basic difference in the VIF-records except for the absence of the initial component (jerk) in the patient. To summarize: a VIF can be elicited in all who can stand and may have largely normal character in a patient without any conventional signs of functioning IA afferents.

DISCUSSION

General nature of the VIF-response

During normal standing in man it has been shown that vibration of certain leg and trunk muscles induces specific sway movements in the sagittal plane which may be strong enough to bring the body off balance. An important question to be answered is whether these sway movements are explicable in terms of segmental tonic vibration reflexes, i.e. can a local change of tension in the muscles stimulated bring about reactions of this type?

Many of the present observations are hard to explain in this way: 1) EMG-recordings from the calf muscles during VSOL revealed no signs of the tonic stretch reflex, which is normally seen in situations when the leg muscles are not engaged in the act of standing. During the backward sway there was instead a gradual reduction of the calf muscle activity like during voluntary backward sway. 2) In patients with total absence of tonic vibration reflexes and Achilles' tendon jerks the VIFs elicitable by VSOL had largely normal appearance. 3) It is hard to conceive that a local vibration-induced contraction in the hamstrings or, even more, in a few segments of the erectores spinae muscles should result in a forward sway of the whole body. 4) The long latency found for the VIF is not compatible with VSOL having elicited a TVR in these initially active muscles.

The above observations indicate that in muscles engaged in the maintenance of the upright posture the vibration-induced tonic stretch reflex is substituted or otherwise concealed allowing other vibration-induced motor phenomena to prevail. These do not appear to be segmentally restricted since they involved widespread "tonus shifts" leading to inclination changes of the whole body in specific directions. It is also extremely unlikely that a segmental inhibition of autogenetic or antagonistic origin should be a common denominator of the reflex adjustments manifesting themselves in VIFs. Thus, TA and HAM are not contracting during the mean posture and a presumed further lowering of the excitability in their motoneuron pools has no counterpart in force changes.

Standing involves a nervous regulation of continuous character and supraspinal coordinative mechanisms serve to ensure that deviations from the wanted position are met with appropriate countereffects. The present results indicate that certain leg and trunk muscles contain vibration-sensitive receptors which during normal standing serve as "error detectors" in this system. The vibratory stimulus inflicts a *false level* in the information and this "error" elicits the VIF-response.

According to Kelton & Wright (17) the tonic stretch reflex is not sensitive enough to control the relative small swaying during ordinary standing and this has been confirmed by Walsh (27) who failed to elicit a response by rapid changes of the angle between the feet and the legs. In Martin's classification of human postural reflexes there are two groups of reflex mechanisms which operate continuously during standing. These are the *anti-gravity* mechanisms and the mechanisms of *postural fixation*, the latter being Martin's descriptive term for the reflex mechanism maintaining a certain relation between two body segments in general. The control of equilibrium belongs to this group in that it involves the relation between the feet and the ground to the rest of the body. The following quotation may serve to illustrate the functional difference between the two main postural reflexes: "The anti-gravity group of reflexes is not concerned with equilibrium, and in fact, as Sherrington found, the decerebrate animal, with its exaggerated anti-gravity activity, is unstable when pushed or tilted and when capsized has no ability to right itself. In diseases of the basal ganglia the anti-gravity mechanism is undisturbed but is unable to maintain the patient's equilibrium". (18). Thus, the VIF-responses are probably a manifestation of the reflexes governing postural fixation including equilibrium and it is also apparent that the tonic stretch reflex is not a fundamental ingredient in these.

General nature of the effects during VIF-counteraction

Information from different afferent sources is used simultaneously to control equilibrium. If the information is reduced, as for example by eye closure, the result is an increased unsteadiness. It may manifest itself in an increased range of the normal swaying movements of the whole body but the concomitant increase in the amount of the DECs is more prominent. Thus, when the task for the equilibrium centres is rendered more difficult the system reacts with an increased "unsteadiness".

The vibratory stimulus used distorts the normal information from a restricted part of the total afferent source which increases the unsteadiness in analogy with the above reasoning (cf. 9). In addition, it is likely that the opposing forces during counteraction add to this increased output. These forces, i.e. the VIF which has a certain strength and direction depending on the vibrated muscles as well as the vibration parameters and the voluntary effort of the opposite direction, are probably somewhat different during short moments although, on the whole, they have the same strength which is apparent from the fact that at least normal subjects can remain in the original position without significant changes of the mean posture. Although the changes in the amount of the DECs may have different causes, the two methods are both suited to measure the strength of the effects of equilibrium produced by muscle vibration. It was found that they gave largely agreeing results as, for instance, when the effect of using different vibration amplitudes was measured. It should be noted, however, that reliable VIF-sway tests are restricted to persons with good ability to remain passive during short stimulation times (not exceeding about 2 s) and that the average value of consecutive VIFs is necessary for critical measurements.

Muscle afferents in equilibrium control

It appears likely that the vibration accomplishes a strengthening of the impulse flow from intramuscular mechanoreceptors which normally serve to measure muscle length and/or tension. This supposition gives rise to a number of questions about how information from different stretch receptors might take part in the control of equilibrium.

The assumption that one and the same receptor group is responsible for the VIF-effects seems justified in view of the relative uniformity of the induced sway regardless of the muscle group vibrated. Which is then the most likely receptor type involved? It was found that vibration of the muscle bellies was significantly more effective than stimulating the distal tendons with the same vibrator parameters. This strongly suggests that the sensory endings in question are in the muscle spindles and not at the musculo-tendinous transition, i.e. the Golgi tendon organs are not the likely receptors. This fact is also in favour of the secondary endings since these are most easily activated by vibration directly over the receptor (2). More evidence for the latter possibility was the findings in the patient in which a damaging factor presumably had destroyed the coarsest nerve fibres leading to complete absence of reflex effects of known primary spindle afferent origin. That patient had VIFs of largely normal appearance, i.e. all the links in the reflex mechanisms including the impulse generation ought to have been intact. Hence it appears that the most likely receptor involved is the secondary endings of the muscle spindles. However, this does not rule out the participation of other types of receptors.

Another important question is whether the afferents in question are tonically active during ordinary standing. Such an arrangement would primarily be in accordance with the general principle about continuous information being used. In agreement with this it was found that the vibration-induced error decreased to zero for an alleged initial average frequency of about 20–30/s. This was the most likely explanation both for extrapolation of the VIF-magnitudes obtained with different, clearly supraliminal stimulus frequencies and from tests with frequency changes to find the threshold for the postural effects. In this connection it is interesting to note that VIFs elicited by VSOL and VTA have much the same magnitude when starting from the mean posture in which SOL is moderately active whereas there is EMG-silence in TA.

What is the content in the information from the VIF-muscles? As regards the leg muscles it is easy to conceive that information about their lengths is transmitted to the equilibration centres. Both VSOL and VTA appeared to "signal" that the muscle group in question was too long since the countereffect, i.e. the VIF, brought about a shortening of the "lengthened" muscles. It is well-known that the secondary endings behave as good length meters whereas the primary endings react to both length and its rate of change. However, these matters become less evident as regards the afferent source above the knee level. HAM and the erectores spinae need not notably change their lengths during swaying of the body and they also differ from the leg muscles in that the concomitant sensation during counteraction was quite different. Thus, it is likely that there is some difference in the functional organization of the postural reflexes elicited from muscles above the knee level as compared to the leg muscles. More knowledge about normal postural regulation has to be available before a complete interpretation of the afferent information can be made.

Vibration of the anterior abdominal muscles as of the knee extensors caused no or insignificant postural effecs and it is natural to ask if this was due to a relative ineffectiveness of the stimulus or if the functional organization is different. It seems safe to conclude that the latter possibility is the more likely. A moderately decreased receptor excitability in response to vibration cannot possibly be an important factor since the maximal frequency and vibration amplitude used means that the speed was at least four times (acceleration 16 times) and the amplitude about twice the threshold as compared to stimulating the other muscle groups. Hence, it is likely that the afferents from the knee extensors and the anterior trunk muscles are not normally included in the afferent source guiding equilibrium.

Many afferent systems are concerned in postural reflexes although it has been concluded that somatic proprioception is the essential one (18). For instance, it is well-known that patients with double leg prostheses can balance quite well despite the lack of information from SOL and TA as well as about the pressure distribution in the soles of the feet. Similarly, blindfolded patients with bilateral vestibular nerve section are little affected during postural activities on a firm base (19). Clinical observations of this kind place somatic proprioception as the most important afferent source by the process of elimination. The present findings are consistent with this fact considering that an "error" from a relatively small part of the possible source so strongly can affect equilibrium.

More findings about the described reflex effects will be given in a subsequent report together with a discussion of additional aspects of the neural regulation of balance during standing.

General aspects of the findings in patients

All patients tested showed an increased amount of DECs. This is consistent with the normal pattern of reaction in response to disturbing or reducing the afferent source. Regardless of whether equilibrium is disturbed due to denervation reducing the afferent information or if some process has affected the central connections, further studies should make possible quantitative measurement of the degree of the disturbance.

The basic VIF-response, i.e. the smooth swaying movements in response to vibration of short duration is generally not suited for quantitative studies in patients. This depends mainly on the fact that vibration brings about gross protective movements of the arms and/or within the body. Due to such protective movements, it was often difficult to detect the VIF although its presence could always be ascertained after some tests, especially by observing the off-sway. Many of the patients had no ability to prevent the fall in the VIF-direction during prolonged vibration despite the use of vision and the prominent "compensating" body and arm movements. In such cases it seemed that the combination of time, vibration and a defective control system eventually made the patient lose his balance.

The present study only presents a few facts about disturbed equilibrium. Further studies of the patterns of reaction of both normal subjects and patients with various disorders are necessary to elucidate more extensively how the postural centres control the act of standing. Other tests than vibration must also be included.

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