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THE ROLE OF THE TONIC STRETCH REFLEX DURING STANDING IN MAN

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ABSTRACT

Relationships between shifts of the center of gravity and electromyographic activities (EMGs) were investigated in man during standing. The EMG was mainly obtained from the gastrocnemius and soleus muscles (GS), but other muscles, such as hamstring, tibialis anterior and quadriceps muscles were also included. The shift of gravity center was measured as a change in foot pressure.

A forward shift of the gravity center by voluntary leaning produced an increase in EMG activity of the GS, whereas a backward leaning caused an opposite effect, i.e., the EMG was suppressed during a backward shift of the gravity center. The same relationship was obtained when the gravity center was shifted by forward or backward pushing of the body.

Rhythmic tilting of the pressure measuring plate, on which the subject was standing, also increased the EMG activity of GS during the forward shift of gravity center, at a tilting frequency of less than 0.5 Hz. However, this relationship was deteriorated when tilting frequency was increased to more than 1 Hz.

When mechanical vibration (100 Hz) was applied to bilateral Achilles tendons, the gravity center was gradually shifted backward and oscillatory flucturation of the gravity center appeared. The EMG activity of GS was not increased by vibration, but decreased in parallel with a backward shift of the gravity center.

The EMG activity of the GS during a forward shift of the gravity center is considered to be due to the tonic stretch reflex caused by stretch of the GS resulting from dorsiflexion of the ankle joint. However, the vibratory stimulus which increases the muscle tone if the GS is not engaged in standing is ineffective in causing the stretch reflex. The failure to observe the stretch reflex by vibration may be explained by assuming that during standing when many other muscle are sending informations on the posture, a functionally heterogenous information, such as the afferent impulses produced by vibration of one muscle, is suppressed at the spirnal cord by a supraspinal center.

INTRODUCTION

During standing in man, the center of gravity is in front of the ankle joints.[1] In the lower limb muscles, the gastrocnemius and soleus (GS) are considered to be activated to prevent the body from falling forward at the ankle joints, and these muscles work essentially under isometric conditions.[2]

In addition, minor corrections of the body position are probably caused by minor changes in the state of the tonic contraction of the antigravity muscles during standing.[3~5] Thus, the tonic stretch reflex (TSR) of these muscles is thought to be involved in controlling the standing posture. But, it seems that the knowledge accumulated has been mostly obtained from animal experiments,[6] and there have been considerable debates[7] regarding the role of TSR in humans. It is natural to assume that the activity of GS is controlled not only by the inputs from the muscles and joints, but also by the inputs from many other receptors, such as the eye and vestibulum. However, the relative contribution of these controlling systems to the maintenance of standing posture is not fully understood.

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In this investigation, the relationship between the electromyogram (EMG) of GS and fluctuation of the center of gravity was investigated in response to three different stimuli, which caused a small disturbance in standing posture in man. These stimuli consisted of forward and backward pushing, vibration on bilateral Achilles tendons, and sinusoidal passive movement of the ankle joints on a force measuring plate.

METHODS

Subjects of the present study were fifteen healthy adults, aged between 25 and 35 years old. They were asked to stand, with their eyes closed except in the second method, on a force measuring plate. The gravity center during standing was recorded with the force measuring place, as a foot pressure (FP), as shown in Fig. 1. The EMG was recorded by cutaneous bipolar leads from the muscles of GS, tibialis anterior (TA), and in some experiments also from the muscles of hamstring and quadriceps.

The experiments were divided into three, depending on the methods of stimulation to produce shifts of the gravity center.

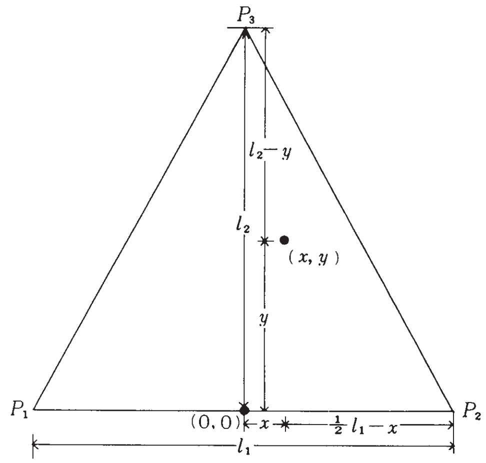

Fig. 1. Principle of obtaining the center of gravity by the measuring plate. The center of gravity of a standing subject can be calculated from the value of the co-ordinates (X, Y) given by the following equation.

$$P_1\,(\tfrac{1}{2}l_1 + x) + P_3 x = P_2\,(\tfrac{1}{2}l_1 - x)$$

$$x = \frac{P_2 - P_1}{P_1 + P_2 + P_3} \cdot \tfrac{1}{2}l_1$$

$$(P_1 + P_2)\,y = P_3\,(l_2 - y)$$

$$y = \frac{P_3}{P_1 + P_2 + P_3}\,l_2$$

The values, P_1, P_2 and P_3 are outputs of the transducer disposed at the respective apexes of the triangle force plate, and the values, l_1 and l_2 are constants (40 cm and 50 cm respectively).

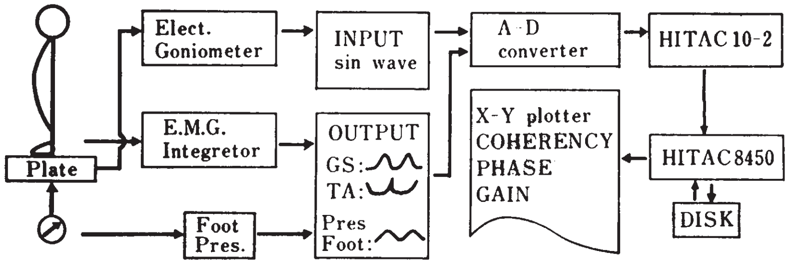

Fig. 2 Signal flow diagram for computer analysis used for the sinusoidal tilting of the force measuring plate. See text for explanation.

1. *Forward push on the back and backward push on the chest*

A rod of about 5 cm in diameter was used for pushing, and the push was maually controlled. Postural adjustments of the standing were analyzed through recording of EMG and gravity center.

2. *Sinusoidal tilting of supporting force measuring plate*

A force measuring plate was inclined ± 5° in the anterior-posterior directions rhythmically with an electric motor via a gearbelt and pulley systems. Thus, dorsiflexion and plantarflexion of the ankle joint correspond to forward and backward shifts of the gravity center, respectively. Care was taken so that the rotational axis of the plate would be identical with that of the ankle joints. Seven different frequencies between 0.1 and 3.0 Hz were used.

3. *Vibration on bilateral Achilles tendons*

A vibrator (HV-2, Heiwa-Denshi) consisting of small, eccentrically loaded DC motors was attached with rubber bands over the Achilles tendon on both sides. The frequency of vibration was about 100 Hz, and its peak-to-peak displacement (amplitude) was 0.2–0.3 mm, and the duration of vibration was for 20–30 sec.

In some experiments, the EMGs of the GS and TA were amplified, full wave rectified, and high frequency component of rectified EMG was cut off by a filter having a time constant of 100 msec or 10 msec, to obtain the intergrated electromyogram (IEMG).

For the analyses of the second experiment, plate angle, IEMG and FP signals were recorded with a data recorder (TEAC 250) and processed off-line by a computer (Fig. 2). The analogue data were digitized with 10 bits, by using an AD converter-controlled minicomputer (HITAC-10), and the digitized data were stored on a digital magnetic tape to process with a large computer (HITAC 8450). Auto correlation and cross correlation functions were computed for the plate angle. The IEMG and FP signals, and these functions were Fourier-transformed to obtain power spectra. Then, the values of the gain and phase were determined, and the coherence functions were also computed.

RESULTS

Responses to forward push on the back and backward push on the chest

Activity of the lower limb muscles was recorded electromyographically during volitional forward and backward leaning (Fig. 3A). The GS and hamstring muscles were activated as the gravity center was displaced forward, and these activities fell off toward the base line as the gravity center returned to the initial position. Similarly, backward leaning activated the TA and quadriceps. There was a good correlation between the degree of leaning and the muscle activity. The activity of antagonists, the TA and quadriceps, was just opposite to that of the GS and hamstring muscles. However, near the maximal leaning, some activities of the antagonists were observed.

Forward push on the back displaced the gravity center temporarily, and the center gradually returned in about 1 sec. There was a concurrent activation of the GS and hamstring (Fig. 3B). On the other hand, backward push on the chest moved the gravity center backward, and activated the TA and quadriceps. When the back was pushed forward, two kinds of EMG responses of the GS were observed in 13 out of 15 healthy subjects. An

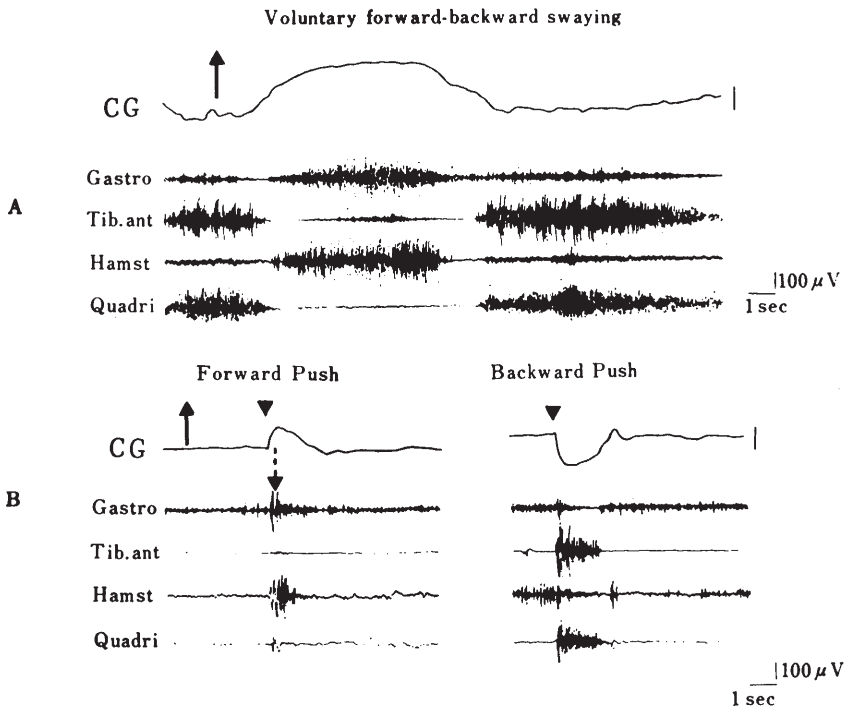

Fig. 3. EMG recordings from lower limb muscles during forward and backward swaying caused voluntarily (A) and by push (B). EMGs of the gastrocnemius and soleus (Gastro) and the hamstring (Hamst) were characterized by a simultaneous increase in activity as the gravity center (CG) was displaced forward. On returning to the standing position, the activities of these muscles fell off toward the base line. Arrows indicate forward shift of CG. Point of push is marked by triangles (▾). The tibialis anterior (Tib. ant) and quadriceps (Quadri) produced opposite activities to those of Gastro and Hamst. Calibration of CG shift; 50 mm.

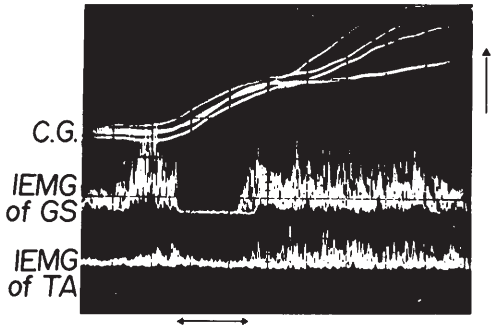

Fig. 4. Forward shift of the center of gravity (CG) (↑) and long-lasting discharge of the gastrocnemius and soleus (GS) induced by forward push on the back. This discharge appeared with a silent period (↔) of about 80–110 msec after the end of initial discharge. The horizontal sweeps were triggered by the push. Notice the similarity in superimposed EMG patterns in four trials. The activity of tibialis anterior (TA) was much less compared with that of GS. The time constant of the filter used for integrated EMG (IEMG) was 10 msec. Calibrations are 15 mm (CG), 100 μV (EMG) and 50 msec (time).

example is shown in Fig. 4. Initial discharges which lasted for about 50 msec were recorded with a latent period of 40–60 msec after the push stimulation, and this was followed by a silent period for 80–110 msec. After this silent period, long-lasting discharges appeared with a latency of 200–230 msec after the push, and it was clear that the late discharge started after the shift of the gravity center.

The late discharges lasted for the period of the forward displacement of the gravity center, and disappeared as the gravity center returned to the initial position. As observed for the voluntary swaying, weak activities of the antagonist muscle (the TA) were simultaneously elicited in response to pushing. In the present experiments, the underlying mechanism of the initial and late discharges was not investigated. However, from these results, it may be concluded that the activity of the GS was determined by a direction of shift of the gravity center, and it was independent whether the shift was caused voluntarily or by pushing.

Sinusoidal tilting of supporting force measuring plate

In this experiment, the subject was asked to hold the standing posture as still as possible on the force measuring plate, which was rhythmically inclined ± 5° at 7 different frequencies. Typical polygraphic recordings obtained at 0.1, 1.0, 1.5 and 2.0 Hz are shown in Fig.5. At 0.1 and 1.0 Hz, the foot pressure changed in parallel to rhythmic tilting of the plate, and forward shifts of foot pressure (i.e., the gravity center) coincided with an increase in the activity of GS, as appeared in the IEMG. However, when the frequency of rhythmic tilting was increased to 1.5 Hz. the response became irregular, and at 2.0 Hz, the foot pressure and the IEMG of the GS showed poor correlation. The EMG activity of the TA was roughly opposite in phase to that of the GS at 0.1 Hz, as observed in response to pushing. However, at 1.0 and 1.5 Hz, they were rather similar in phase, and at 2.0 Hz

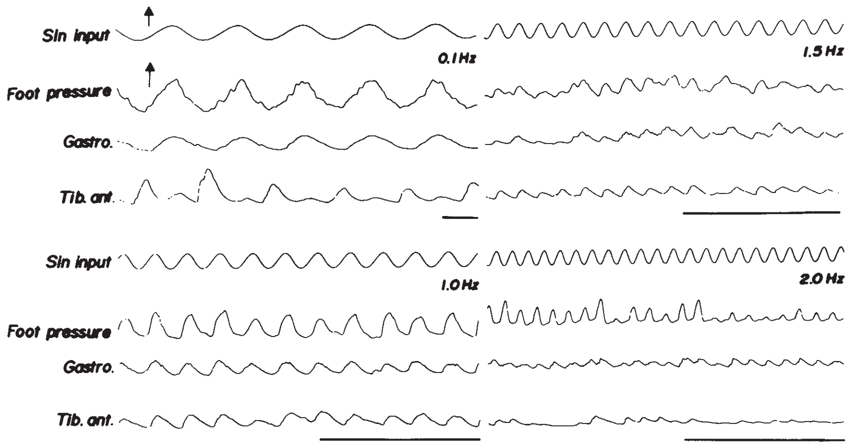

Fig. 5. Typical polygraph records showing responses of foot pressure (as indication of the gravity center) and IEMG of the gastrocnemius and soleus (Gastro.) and tibialis anterior (Tib. ant.), produced by sinusoidal change in angle of pressure measuring plate (± 5°, sin input) at 0.1, 1.0, 1.5, and 2.0 Hz. For IEMG, high frequency was cut off by a filter having a time constant of 100 msec. Calibration for foot pressure corresponds to 10 mm shift of the gravity center, 200 μV for IEMG and 5 sec for time. Dorsiflexion (↑) caused by tilting the plate coincides with a forward shift (↑) of the foot pressure at 0.1 Hz.

no apparent correlation was found between the responses in the TA and the GS.

The data obtained were analyzed by a frequency response function commonly utilized in the field of human engineering.[8,9] Figure 6 shows the phase and gain relationships with the input signal of tilting of the force measuring plate. The phase lag of the foot pressure and IEMG activities increased from 0.5 to 2.0 radian as the input frequency increased from 1.0 to 2.0 Hz, and the phase lag of foot pressure response was greater than that of IEMG response at an input frequency of 0.5–1.5 Hz. The gain of both foot pressure and IEMG responses also decreased with increasing frequency, but the decrease in the gain of IEMG response was greater than that of foot pressure. The gain of IEMG decreased rapidly from −5 to −15 dB as the input frequency increased from 1.0 to 2.0 Hz, whereas the gain of foot pressure still remained −5 dB at a frequency of 2.0 Hz.

A coherence function was normalized between 0 and 1.0. The values of this function in the GS demonstrated the linearity of this system, since these values were generally around 0.8 to 0.9. The coherence values of the TA activity were very low (about 0.2 – 0.5), and the data obtained were considered to be insignificant.

Responses to vibration on bilateral Achilles tendons

In all of the subjects, the vibratory stimulus on bilateral Achilles tendons resulted in backward displacement and then periodic oscillation of the gravity center during the vibration (Fig. 7). When the vibration ceased, a large forward displacement of the gravity center was transiently elicited with a short delay.

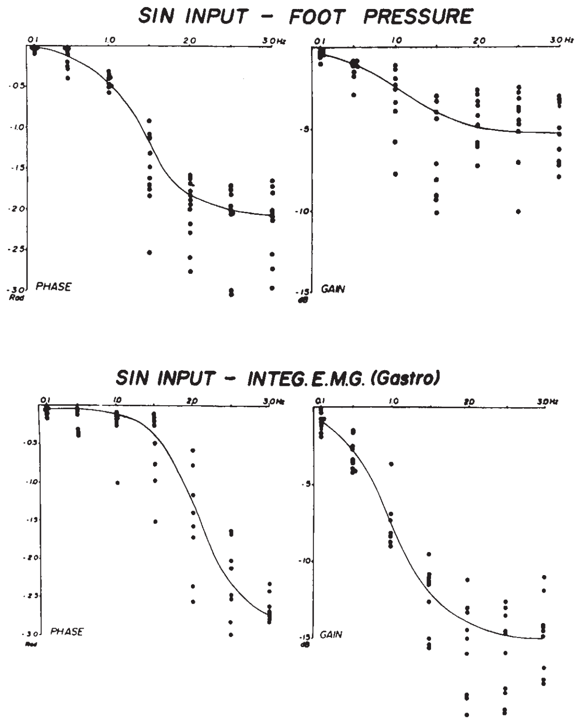

Fig. 6 Frequency response curves of foot pressure and integrated EMG of gastrocnemius and soleus (Gastro.) responses for phase and gain. The values shown by dots were obtained from 8 dirrerent subjects, and the average was expressed by the curve.

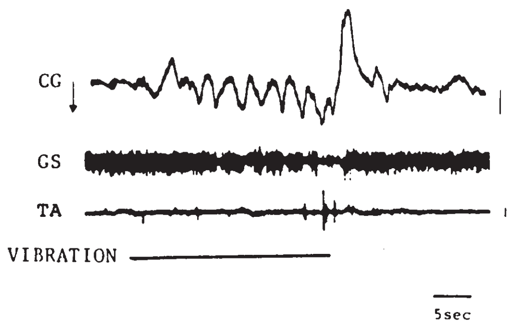

Fig. 7. EMG responses of the gastrocnemius and soleus (GS) and tibialis anterior (TA) to vibratory stimulation applied for 25 sec (shown by the horizontal bar). Note gradual backward shift (↓) and oscillation of the center of gravity (CG) during vibration. Calibrations are 10 mm (CG), 100 μV (EMG).

The vibration was usually applied for 20–30 sec, because if stimulated over 1 min, the subjects were unable to maintain natural standing posture and they actively tried to lean in a direction opposite to the deviation to keep from falling. Such active compensation was not produced with a short stimulus duration of about 30 sec. The subjects only noticed vibratory sensation of Achilles region and were not aware of the resultant backward deviation of the gravity center.

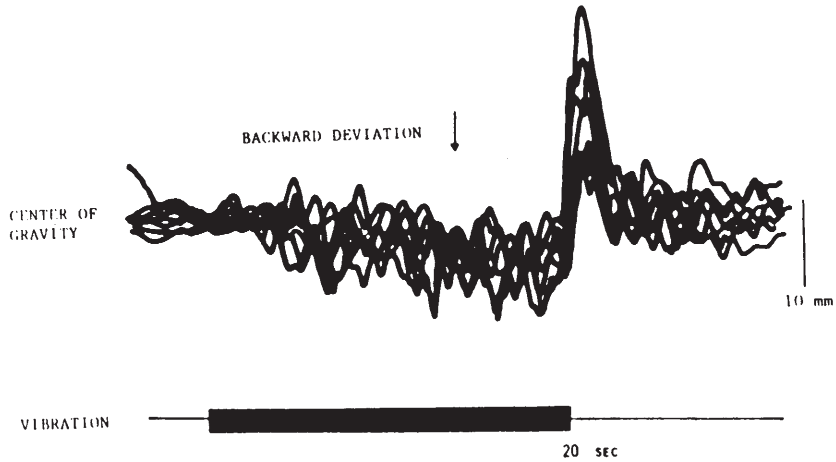

Fig. 8. Postural responses to vibratory stimulation (100 Hz), for 20 sec (as shown in the lower trace) obtained from the same subject as for Fig. 7. Seven successive traces were superimposed.

During a backward shift, there was a gradual reduction of the GS activity. When the backward shift became more than 1 cm, the activity of the GS was suppressed and some activity was elicited in the TA.

The response to vibration was irregular, but the general pattern was rather constant, as seen in the superimposed figure (Fig. 8). The backward shift occurred gradually, taking 5–15 sec to reach a steady state. The frequency of periodic oscillation of the gravity center was almost constant in the same subject, ranging from 0.3 to 1.0 Hz.

DISCUSSION

The activity of the GS, as measured with EMG, is well correlated with the shift of the gravity center. The activity is increased with a forward shift, while it is decreased during a backward shift of the gravity center. This relationship is the same both for the voluntary leaning and for the shifts produced by various external disturbances. If the GS contracts to compensate the forward shift of gravity center, it would be expected that the activity starts near the peak of the forward shift and that the activity is maximum during the returning process of the shift. However, the activity starts nearly simultaneously with a forward shift of the gravity center and the activity is highest during the maxium sway. Thus, the GS does not seem to be actively contributing to the body sway, but the activity of the GS is probably reflexively controlled by a forward movement of the gravity center.

It is possible that a forward tilting of the lower limbs (i.e., dorsiflexion of the ankle joint) stretches the GS and increases its activity due to the tonic stretch reflex (TSR). However, this idea is not supported by the results obtained from the vibration experiments. It is known that muscle vibration is an efficient stimulus for the human muscle spindle, and that this stimulation causes an increase in muscle tone by the TSR, under the condition in which the muscle is not engaged in supporting the body.[10~12] On the contrary, when the muscles are engaged in supporting the body, the muscle vibration does not produce the increase in muscle tone, probably due to suppression of the TSR by a supraspinal center working for equilibrium.[13,14] This has been confirmed in the present experiments. Vibration of the GS produces backward shift of the gravity center and a decrease in the EMG. Thus, it seems that the TSR is not functioning in the standing posture, at least under this experimental condition.

This apparent discrepancy concerning the TSR between the forward sift of gravity center and the vibratory stimulus may be explained by the following hypothesis. During standing, the equilibrium center is informed from various sources, such as the muscle spindles, the receptors of joints and skin of lower limbs, and also vestibular and visual receptors. Although their relative importance in controlling the posture is not known, all their informations are considered to be integrated to control the individual muscles. In other words, the activity of motoneurons in the spinal cord is determined by integrative actions of the supraspinal center depending on the various postural information.[15] During swaying, the afferent impulses from the GS are functionally in accord with the affenrent impulses from all other sources in informing the equilibrium center as to the changes in posture. Under this condition, the afferent impulses of the GS naturally cause the TSR. On the other hand, when vibratory stimulus is applied only to the GS during standing, the afferent impulses from the muscle spindle of the GS would inform the higher center as if the muscle were stretched, but this information disagrees with other informations sent by other receptors. It is possible that such a functionally heterogenous information cannot be utilized for the TSR due to suppression by the higher center.

Changes of ± 5° in the ankle joint correspond to approximately ± 5° mm of the GS (i.e., about ± 2.5 % of total length of the muscle). Thus, the rhythmic tilting is enough stimulus for the muscle spindle and the forward shift of gravity center corresponds to the phase of stretching the GS. Therefore, the EMG activity during the forward sway in rhythmic tilting is probably a result of passive stretch of the GS. Since changes in the foot pressure are more likly passive, i.e., the muscle contraction is not actively contributing to the sway, the frequency responses of phase and gain of the foot pressure in tilting seem mainly to represent physical properties of the body. On the other hand, the frequency responses of the EMG activity of GS may be determined by the integrative function of the central nervous system. When the tilting frequency is increased the gain response of EMG is markedly reduced at around 1 Hz, and the decrease is much greater than that of the foot pressure.

Although the underlying mechanism determining these frequency responses is not known, it is interesting to apply this method of analysis as a neurological test at the clinical level. It is hoped that this kind of approach utilizing the external disturbance in standing posture may throw light on a control mechanism of posture reaction.

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