Human Posture Dynamics in Response to the Horizontal Vibration

Young-Kyun Shin*, M. A. Fard**, and Hikaru Inooka **

* Graduate School of Information Sciences, Tohoku University, Aramaki aza 01, Aoba-ku, Sendai 980-8579, Japan
(Tel : +81-22-217-7021; E-mail: ykshin@control.is.tohoku.ac.jp)
** Graduate School of Information Sciences, Tohoku University, Aramaki aza 01, Aoba-ku, Sendai 980-8579, Japan
(Tel : +81-22-217-7021; E-mail: {fard, inooka}@control.is.tohoku.ac.jp)

Abstract: The functional behavior of each body segments were investigated with respect to human standing posture when they were exposed to the horizontal vibration in the sagittal plane. This study is processed by experimental approach. The data is analyzed, both in the time domain and in the frequency domain. Random and multisinusoidal vibration was used as input. The ankle, hip, and head were employed as the significant body segments. High relative movements were present between hip and head, and there was no significant relationship between ankle and head. Variations of visual input produced a significant postural effect..

Keywords: Human standing, Horizontal translation, Cross-correlation, Vision.

1. INTRODUCTION

Human standing is thought to depend on the interaction of multiple sensory system involving visual, vestibular and somatic inputs. From a mechanical perspective, the human skeletomotor system is poorly adapted to the preservation of a vertical posture due to its multi-segmented nature, the high position of the centre of mass, and the small base of the support. However, the multijoint design of the body allows balance to be maintained in a variety of body configurations, as well as during movement. Thus, despite the mechanical complexity of body, it is surprisingly stable, and the central nervous system has the ability to coordinate posture and movement or, more generally, to combine mobility with stability.

The inverted pendulum model is often used for standing posture study. Horak and Nashner [1] defined the ankle and hip strategies based on a combination of electromyogram, force plate and kinematic patterns. McCllum and Leen [2] showed that stiffening the body so that it acts as a one-segment inverted pendulum (as in the ankle strategy) provides a longer time constant than if the body is stiffened as a two-segment inverted pendulum (as in the hip strategy).

When stable standing body is exposed to the external perturbation, the each body segments generated reactionary movements for maintaining postural balance. During this processing, there is an interaction and a synergy between each body segments. The presence of body segments movement, it may reflect that relative role of each body segments, and suggest the disturbances may be compensated for standing balance.

There are two major standpoint when the standing body is exposed to the external perturbation; (1) the external disturbances are actively damped by the central nervous system (CNS), or (2) it is passively damped by viscous properties of skeletal muscles without intervention of a control system. The visual, vestibular and somatosensory feedbacks are included in the CNS. If the external disturbances damped actively as the result from the reciprocal behavior of the different body segments, movements of body segments should be occur in phase with platform movements, and these movements should be coordinated. The weight of the anticipatory reactions is probably maximal under conditions of known type and timing of the platform displacement (Nashner et al. [3], Horak et al. [4]).

Although a number of studies have investigated postural control in response to external disturbances, few reports exist to explain explicitly how subjects behave under such circumstances (Tokita et al. [5], Diener [6], Dietz et al. [7]).

In the present study, we investigated the functional behavior of each body segments when standing body exposed to the horizontal translation in the sagittal plane, placed on a triangular foot, at frequency ranging from $0.1Hz$ to $3Hz$. The model is not purely based on inverted pendulum body dynamics, but rather on a three-link segment model of a standing human on a movable support base. This study is processed by empirical approach. Random and multisinusoidal vibration was used as input. The data is analyzed, both in the time domain and the frequency domain.

2. EXPERIMENTS AND METHODS

2.1 Subject

Four healthy individuals participated in this study (mean age $\pm$ SD 28 ± 2.6 years). No subjects had any evidence or history of neurological, gate, postural or musculoskeletal impairments. All participants gave their informed consent prior to inclusion in the study. All subjects completed all trials without falling, stepping or reaching for a stable support.

During the experiment (Fig. 1), each subject was instructed to stand upright on the platform in a standardized stance, and the subject's feet were separated medio-laterally by a distance about $10cm$, and to keep it together so that the left and right ankle joints rotate about the same axis and particularly noticed keeping the knees straight. The subject eyes were either open (EO) and fixed upon a target at eye level, or closed (EC), depend on the requirements of the specific trial.

After each trial, intervals were included to avoid subject's exhaustion. The subjects stood barefoot with their arms folded comfortably across the chest and their head facing forward and upright. This arm position was adopted in order to eliminate the possibility of the arms entering into the dynamics. The condition of the feet that were assumed not to slide or lift at the heel or toe, and since the triangular foot model is considered, it did not enter into the dynamics of the system.

2.2 Movement analysis

Kinematic data were collected using a Vicon movement analysis system (Vicon 460, Oxford Metrics Ltd.) with six cameras situated $1.5-2m$ from the subject. Data were sampled at $120Hz$ and simultaneous inputs from the cameras were automatically converted into three-dimensional coordinates using Vicon software. Calibration was performed using a fixed frame with five markers and a bar fixed with two reflective markers with known dimensions. Fifteen reflective markers ($25mm$ diameter) were placed over surface landmarks to monitor motion of the each body segment. (Fig. 1)

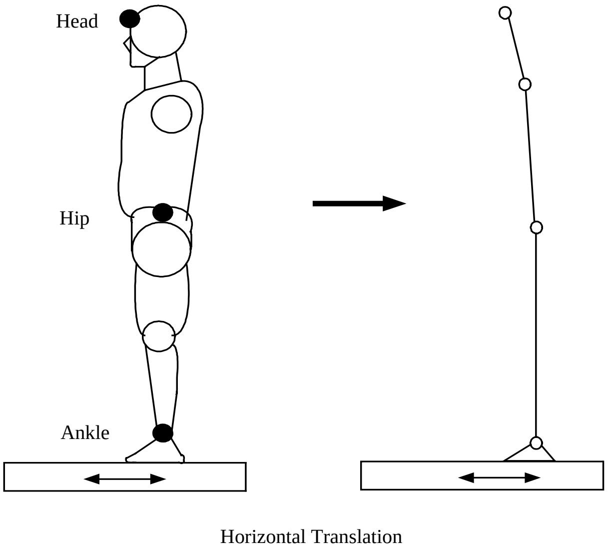

Fig. 1 The schematic of human standing posture exposed to the horizontal vibration**.**

2.3 Servo-controlled vibrator

AC Servo-motor controlled vibrator was designed as a mobile platform. Two vibration series were devised. Zero mean Gaussian random and multisinusoidal horizontal translation; random (generated mean stroke was 13 mm, and generated mean acceleration was $2.58m/s^2$), multisine (generated mean stroke was 20 mm, generated mean acceleration was $2.46m/s^2$). The platform has Max frequency as $5Hz$, and Max. Load. as $100kgf$. These two input were devised for testing severe conditions which could generates near the limits of the displacement of each body segments. The initial period was not acquired to eliminate from the acquisition non-stationary events possibly induced by the onset of platform translation.

3. RESULTS AND DISCUSSION

3.1 The reaction of the body to the platform translation

The typical time course of the displacement with different vibration is shown in Fig. 2, for one representative subject. This figure provide the displacement of each body segments, when subject is exposed to zero-mean Gaussian random and multisinusoidal horizontal perturbation with eyes open (EO) and eyes closed (EC) at frequency range from $0.1Hz$ to $3Hz$. Each graph indicates the response of the three body segments (ankle, hip and head) in the sagittal plane; random (Fig. 2A) and multisine (Fig. 2B); ankle (bottom traces), hip (middle), and head (top). The solid line indicates the response of each body segment with EO, and the dotted line follows EC.

The displacement of vertical direction in each graph, points to the forward (FW) and backward (BW) direction. Note that the scale of the ordinate in Fig. 2A is two times larger than Fig. 2B. The displacement of ankle was always equal to the trace of platform in all trials, so it was perfectly mirrored the trace of the platform itself, as given that no relative movement of the foot with respect to the platform occurred. The peak-to-peak displacement of hip and head varied, however, depends on both the visual series and the type of vibration. A progressive amplification from the perturbation effect was present between EO and EC.

Fig. 3 was derived from traces analogous to those presented in Fig. 2. It shows schematically the average peak displacement of the different body segments during each trial, under EO and EC, for both translation series. Take notice that the displacement of the designed stroke in multisine vibration is little bit larger than that of random. It's due to the multisine movement of the supporting platform needs more larger displacement for generating more severe postural perturbation.

Clearly, (1) In random perturbation, since the subject was exposed to the random perturbation, its intermediate frequencies were not easily perceived to the subject and they couldn't adapt their standing posture to the irregularly changing profile of platform, anticipating it was also difficult; (2) though predictable, however, the subject can withstand relatively stable in the condition of continuous periodic platform oscillating (i.e. multisine); (3) on average, the displacement of hip was smaller than that of the ankle in EO, while it varied to increase in EC;

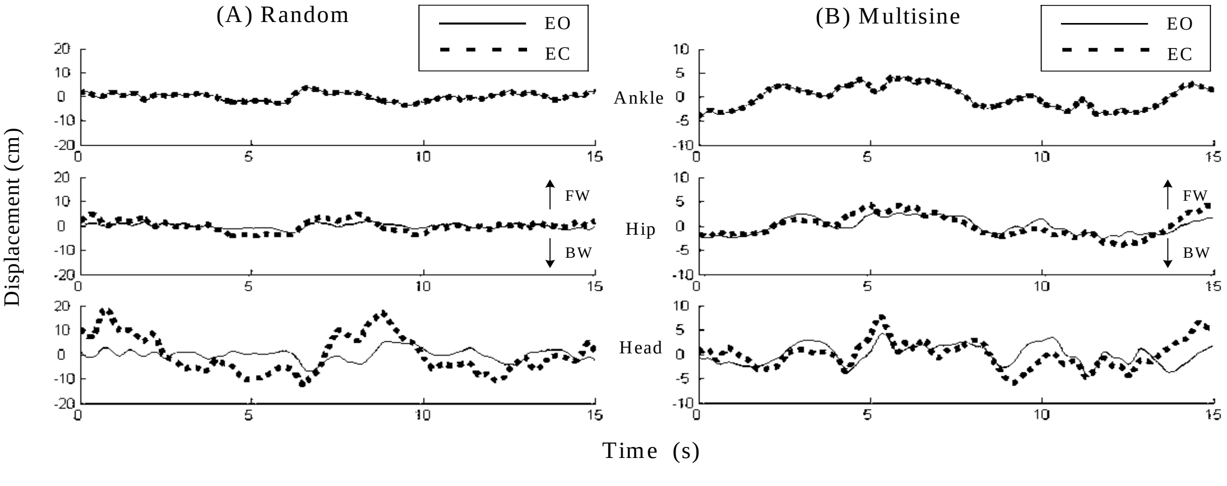

Fig. 2 Time course displacement of each body segments in the sagittal plane; Input: (A) random, (B) multisine; eyes open (EO), eyes closed (EC) ; forward (FW), backward (BW). Note that the ordinate of (A) is two times larger than (B)

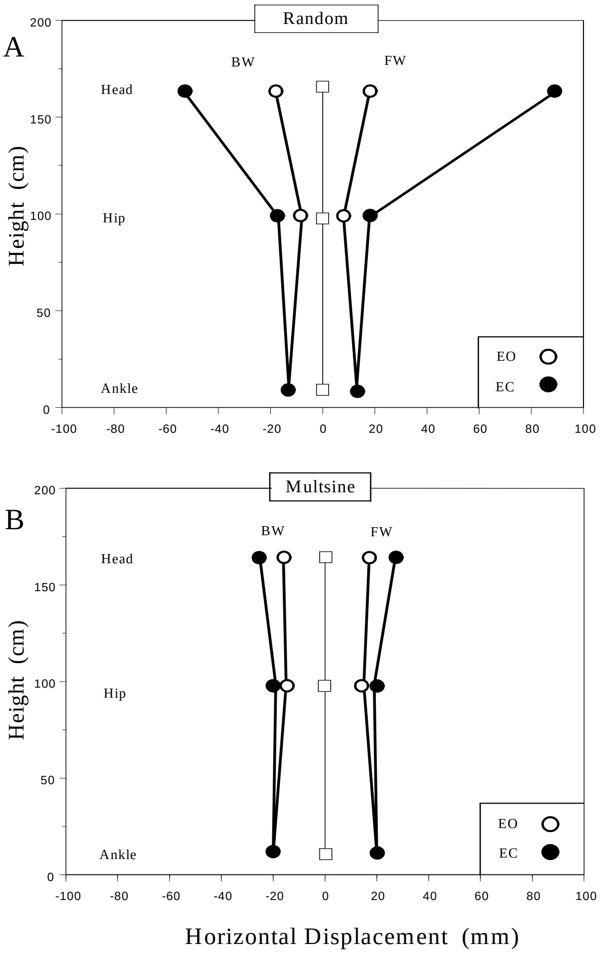

Fig. 3 Antero-posterior displacements of the markers positioned at ankle, hip, and head under eyes open (EO) and eyes closed (EC).

(4) the oscillation of head was decreased at the periodic input, particularly, it showed up when visual condition was changed. In other words, the body was thrust beyond the limits of platform excursion with EC, while head displacement minimized with EO. Correspondingly, since the motion of the hips also causes relatively large movement of the head, and thus may effect vestibular sensors within the skull, which may have implications on sensory feedback to the nervous system; (5) the displacement of head was larger in the forward than backward direction, possibly due to the large size of the foot support base in front than behind the ankle and, the hip was kept within the limits of platform excursion with EO, even at the random translation.

3.2 Cross-Correlation Analysis

To understand its functional behavior caused by the acceleration, relates each body segments in standing postural balance, we processed cross-correlation (CC) analysis. The correlation coefficient, symbolized by the R, which ranges in value from $R = 1$ for a perfect positive correlation to $R = -1$ for a perfect negative correlation. The coefficient of determination, symbolized as R^2 , which is simply the square of the correlation coefficient.

The coefficient of determination can have only positive values ranging from $R^2 = 1$ for a perfect correlation (positive or negative) down to $R^2 = 0$ for a complete absence of correlation. The advantage of the correlation coefficient, R , is that it can have either a positive or a negative sign and thus provide an indication of the positive or negative direction of the correlation. The advantage of the coefficient of determination, R^2 , is that it provides an equal interval and ratio scale measure of the strength of the correlation. In effect, the correlation coefficient, R , gives you the true direction of the correlation but only the square root of the strength of the correlation; while the coefficient of determination, R^2 , gives us the true strength of the correlation but without an indication its direction.

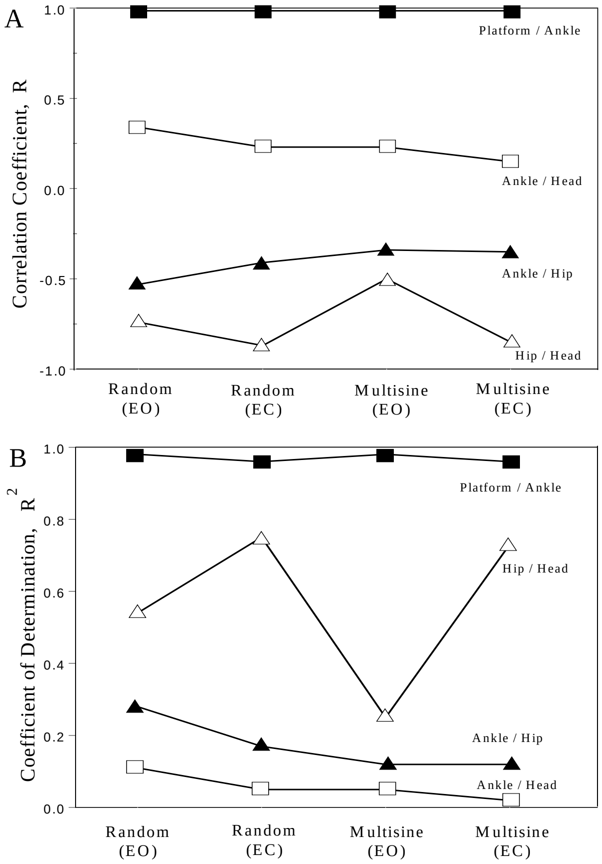

Fig. 4 Traces of the mean cross-correlation value between different body segments. (Acceleration data)

Fig. 4 shows the correlation coefficient, R (Fig. 4A), and the coefficient of determination, R^2 (Fig. 4B). These CC profiles for the four pairs of body segments (platform/ankle, ankle/hip, ankle/head, and hip/head) averaged across all subjects for both visual series and type of translation. There was the significantly high R value in the pair platform/ankle under all trials, not only variation of visual series (EO and EC) but also the random and the multisinusoidal input, it is closed to 1 with positive direction. This value represents that the displacement of ankle is always equal to throughout the whole period of the platform motion.

The low R values were observed in all trials in the pairs ankle/hip and ankle/head, with negative and positive direction respectively, and both results are relatively closed to zero in multisinusoidal translation with EC (ankle/hip: $R = -0.35$; ankle/head: $R = 0.15$). Across the abscissa of Fig. 4A, i.e., under the variation of vision (EO and EC) and type of translation (random, multisine), these pairs show moderate traces, while the pair hip/head represents sudden profile. Though it oscillated under different conditions of each trial, clearly, there were the high R values in the pair hip/head, with negative direction.

From the coefficient of determination, R^2 (see Fig. 4B), the strength of the correlation between each body segments, in response to horizontal perturbation, can be estimated effectively. The pair ankle/head showed significantly low values of R^2 among different body segments pairs, especially it approached near to zero when subjects were exposed to multisinusoidal perturbation. The value was calculated less than $R^2 = 0.1$. The R^2 values of the pair ankle/hip was a little bit higher than the pair ankle/head, it also showed relatively low values compare with the other pairs.

The result of CC profiles indicate that the absence of consistent behavior of the hip across the platform displacement, and an independent motion between ankle (lower limb) and hip (trunk) segments when standing posture was exposed to the horizontal vibration. Meanwhile, as it proved, high relative movement existed between hip and head, while there were no significant relationship between ankle and head.

3.3 Functional Interpretation in Frequency domain

Since we were dealing with a random phenomenon, and the platform translations produced corresponding displacements of the body segments, we analyzed the data signals not only in the time domain, but also in the frequency domain. The correlations between different body segments (ankle/hip, ankle/head, and hip/head) in the frequency domain, that is, coherency, are presented in Fig. 5, for one representative subject from the calculated acceleration data; random with EO (Fig. 5A), random with EC (Fig. 5B). Figure 6 provides the mean coherency results. It is averaged across all subjects.

Coherency provides a formal measure of the correlation between the two signals in the frequency domain. A coherency of 1 indicates that the phase shift between the waveform at a given frequency is constant, and the amplitude of the signals at that frequency has a constant ratio (Bendat and Piesol [8]). In addition, if the system is linear and input-output signal is not corrupted by noise, the value of coherency will be closed to 1. In general terms, coherency is a measure of the presence of a constant temporal (phase-locked) and spatial relationship between the phasic changes in two signals.

In here, the coherency was calculated from the cross-spectral density between the acceleration data of different body segments which were normalized by the power spectral density of each waveform. As expected, the position of the maximum coherency varied with the frequency band of the different pairs and the type of horizontal translations. For instance, when vision was allowed (Fig. 5A), the highest degree of coherency was found from 1.6 to $2.1 Hz$ in all body segments pairs, and the pair ankle/head presents the lowest value from 0.3 to $0.4 Hz$. When vision was denied (Fig. 5B), in all pairs of body segments, the lowest value was observed in 0.4 to $0.6 Hz$ and 1.1 to $1.6 Hz$, while the frequency range from 1.6 to $1.8 Hz$ shows the highest value.

The high coherency was present in random with EO (Fig. 5A) comparing with random with EC (Fig. 5B). The mean coherency values expand this point with respect to the all pairs of the body segments. It was estimated to be greater than 0.85 (see Fig. 6).

In random with EC condition, these three pairs revealed more clear differences of the maximum coherency values. The

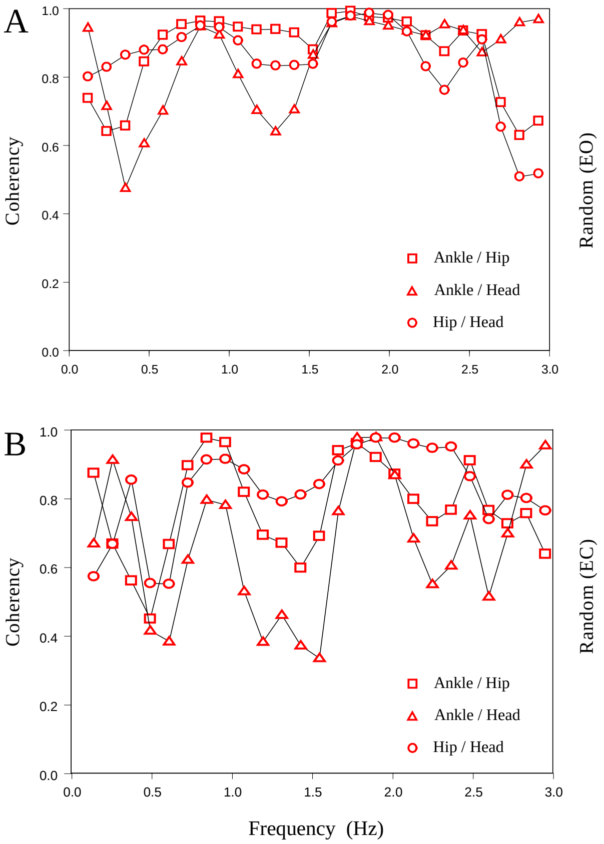

Fig. 5 Frequency analysis of the each different body segments.

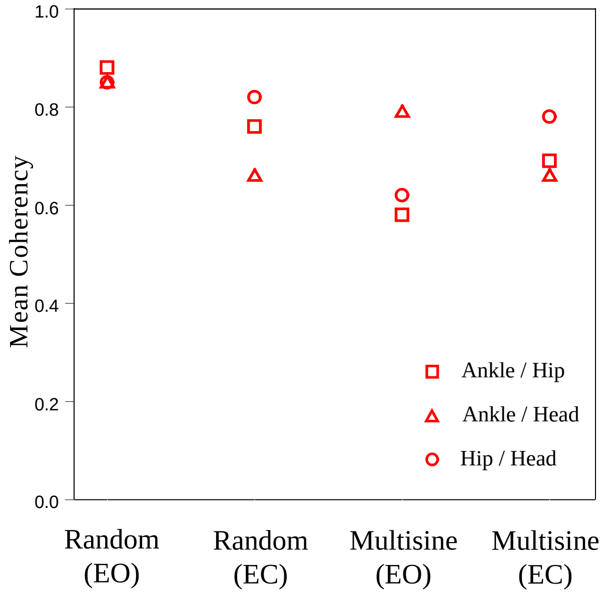

Fig. 6 The mean coherency values in random horizontal input.

pair hip/head was presented as the maximum, and ankle/head showed as minimum. This pattern corresponds with the result of time domain analysis. The traces of the pair ankle/head were most fluctuated across the variation with frequency range in random translation (EO and EC). It is because that head were most affected by vision.

There are two major standpoint relates when the standing body is exposed to the external perturbation; (1) the external disturbances are actively damped by the central nervous system (CNS), or (2) it is passively damped by viscous properties of skeletal muscles without intervention of a control system. The visual, vestibular and somatosensory feedbacks are included in the CNS. If the external disturbances damped actively as the result from the interactional behavior of the different body segments, movements of body segments should be occur in phase with platform movements, and these movements should be coordinated.

In here, the high value of coherency indicates that the phase relationship and the ratio in each pair of the body segments are relatively constant. In other words, the different pairs of body segments are (ankle/hip, ankle/head, and hip/head) more correlated under such circumstances, and the external disturbances are might be damped mainly by the CNS. On the contrary, the low values of coherency presents that the external excitations are might be damped by leading from skeletal muscles effects. Partially, the result of random series follows this point in Fig. 5 and Fig. 6; note that, relates to the human posture dynamics, the effect from the musculoskeletal dynamics and the CNS always significantly coexist. In comparison between EO and EC, the coherency values of EO condition showed higher values than EC condition. Moreover, the pair ankle/head showed most fluctuated traces.

However, the coherency of multisinusoidal input showed different patterns with that of random conditions (see Fig. 6). When stable subject standing is perturbed by a random translation, since its intermediate frequencies were not easily perceived to the subject, he couldn't adapt the body balance to the irregularly changing profile of platform, anticipating it was also difficult. However, when subject stands on a platform undergoing a multisinusoidal excitation, since it is a periodic, he can easily withstand a condition of continuous postural perturbation. Furthermore, they succeed in minimizing the centre of mass displacement by adopting an appropriate behavior, flexible and compliant with the particular vibration conditions. The flexibility of the behavior appears to imply a combination of the two basic ankle and hip strategies [1]. Moreover, the weight of the two strategies changes with changes in the frequency of translation or visual condition.

4. CONCLUSION

The functional behavior of each body segments was investigated with respect to the standing body exposed to the horizontal translation in the sagittal plane. This study was processed by experimental approach. When stable upright stance was disturbed by random translation, its intermediate frequencies were not easily perceived to the subjects and they could not adapt their body balance to the irregularly changing profile of platform, anticipating it was also difficult. Though predictable, however, the subject could withstand stably in a condition of continuous periodic platform oscillating.

The displacement of ankle was always equal to the trace of platform in all trials, so it was perfectly mirrored the translation of the platform itself. Variations of visual input produced a significant postural effect. The oscillation of head was larger in forward than backward direction, and it was decreased at the periodic translation. The cross-correlation result indicated that high relative movement exist between hip and head while there was no significant relationship between ankle and head. The frequency domain analysis was consistent with the time domain results in the random translation when the vision was allowed. However, the result of multisinusoidal exciation did not consistent this pattern because the subject could predict the perturbation.

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