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Open Loop Responses of Posture Complexity in Biomechanics

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Abstract

The reactionary responses to control human standing dynamics were estimated under the assumption that postural complexity mainly occurs in the mid-sagittal plane. During the experiment, the subject was exposed to continuous horizontal perturbation. The ankle and hip joint rotations of the subject mainly contributed to maintaining standing postural control. The designed mobile platform generated anterior/posterior (AP) motion. Non-predictive random translation was used as input for the system. The mean acceleration generated by the platform was measured as 0.44 m/s^2. The measured data were analyzed in the frequency domain by the coherence function and the frequency response function to estimate its dynamic responses. The significant correlation found between the input and output of the postural control system. The frequency response function revealed prominent resonant peaks within its frequency spectrum and magnitude. Subjects behaved as a non-rigid two link inverted pendulum. The analyzed data are consistent with the outcome hypothesized for this study.

Key Words : Coherence Function, Frequency Response Function, Non-predictive Horizontal Vibration, Resonance Frequency, Standing Postural Control

1. Introduction

The postural mechanism for equilibrium control of human standing has attracted the attention of many researchers in the field. Understanding the mechanism of postural dynamics is important for several reasons. First, it allows a biomechanical point of view to unfold the complexity of sensorimotor control. Second, it can facilitate the approaches of preventing risk to health and its management, new designing of prostheses and rehabilitation. Third, it can stimulate design ideas for robots that can have greater capability in controlling balance.

Many researches exist in the field that have proven useful for the analysis of the responses of human standing postural control, such as perturbations to the proprioceptive subsystem [1-3]

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and perturbations to the vestibular subsystem [4-5]. These studies have investigated the significant role in elucidating the contribution made by different subsystems to overall equilibrium control.

The study of transient perturbation to evoke characteristics of postural responses [1-2] may be useful to demonstrate trigger specific and equally transient motor programs with respect to the standing posture mechanism. However, this may not be directly related to the continuous regulation of postural balance control. Hence, the use of continuously-applied perturbation may be appropriate to study postural control behavior, which itself is a continuously maintained process.

Since the complexity of the biomechanics of the human standing posture dynamics, through the restriction of the subject standing body conditions as a low degree of freedom, simplification of the system is essential for understanding the basis of biomechanics of standing posture complexity. The resonant behavior of the different parts of the human body at some frequencies can further suggest taking the frequency-domain responses of the human body into consideration.

Steady-state stimulus-response data can be used to obtain transfer functions that characterize the dynamic properties of the system [6]. These methods have been used previously to investigate postural control in humans [4, 7-10] but have not been systematically applied to investigate dynamic behavior over a wide range of conditions.

Three significant assumptions were adopted in this study. Firstly, the motion of standing posture complexity mainly occurs in the sagittal plane. Secondly, the standing posture complexity only has flexion/extension motion, so that the translational motion of standing posture complexity is assumed to be negligible. Thirdly, during AP platform motion, the subject's knee is tightly fixed, so ankle and hip joint rotation were assumed to contribute to maintaining balance. To analyze the dynamic behavior of human standing control, the coherence function and the frequency response function were estimated over a frequency range from 0.2 to 3 Hz.

2. MATERIALS AND METHODS

2.1 Subject

Experiments were performed on four healthy participants (mean age ± SD, 27.5 ± 5.2 years), with physical information given in Table 1. None of the participants reported any history of neurological, otological, or orthopedic abnormalities.

Since this study hypothesized that the ankle and hip joint were the major joints compensating for external perturbation, the other joints, i.e., knee, neck were tightly fixed (Fig. 1). A number of fixing assemblies (medical appliances) were used, including medical splints and casts, and Velcro straps, to provide rigidity in these joints. The head, trunk and lower extremity of subjects were not separately movable, which means that subject posture could be controlled as an inverted pendulum. During the experiment, the subjects' bodies were extremely restricted, making them unable to tolerate a long duration under experimental conditions. Thus, sufficient rest intervals were given to avoid subject exhaustion after each trial.

Table 1. Physical characteristics of the subjects (# sign indicates the subject number)

Subject	Age (yr)	Height (m)	Weight (kg)
#1	23	1.70	65
#2	23	1.68	58
#3	32	1.74	64
#4	32	1.74	75
Mean (SD)	27.5 (5.2)	1.72 (0.03)	65.5 (7.05)

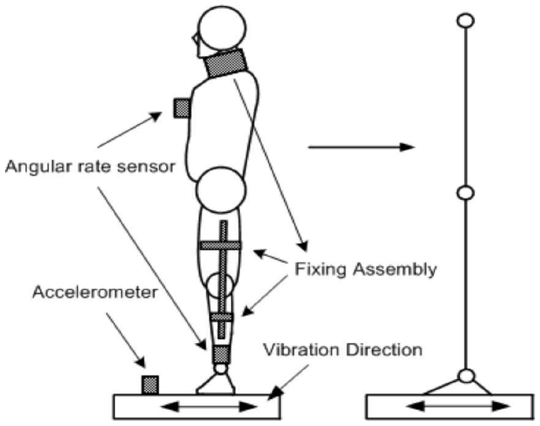

Fig.1. The schematic of human standing posture exposed to horizontal vibration

The participants were informed to stand upright and were barefoot. The feet were placed slightly less than shoulder width apart by a distance of about 10 cm, and kept together so that the left and right ankle joints rotated around the same axis.

Falling or stepping on the platform were prevented, and the feet were assumed to have not slid or lifted at the heel or toe. Since a triangular foot model was considered, it did not enter into the dynamics of the system. Arms were folded comfortably across the chest, and heads faced forward and upright. These arm and head positions were adopted in order to eliminate the possibility of their arm and head sway entering into the dynamics. Across all trials, room lights were off, and participants were blindfolded and instructed not to resist or apply any voluntary response.

2.2 Experimental setup

The AC Servo-motor controlled vibrator was designed as a mobile rigid platform. The vibrator system consists of an AC Servo-motor (Sanyo-Denki Co.) and actuator unit (THK Co.). It had a maximum stroke of 1200 mm, maximum frequency of 5 Hz, and maximum Load of 100 kgf.

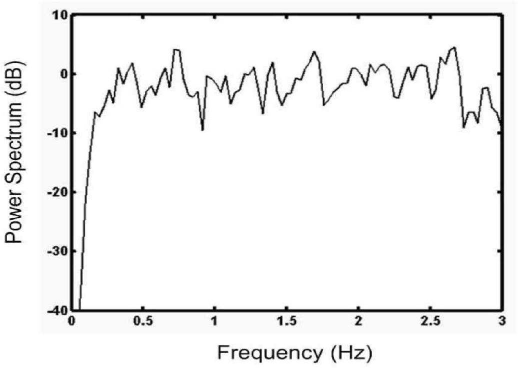

Fig. 2. Power spectrum of the input acceleration

The platform had a size of 606×406 mm. Zero mean Gaussian random vibration was devised as the input. It generated a mean stroke of 0.03 m, and mean acceleration of 0.44 m/s^2.

The power spectrum of the input signal is shown in Fig. 2. This input was devised for testing severe conditions that could generate near the limits of human standing posture. The duration of each trial was 40 s. The initial period was not acquired in order to eliminate from the acquisition non-stationary events possibly induced by the onset of platform translation. Thus, data from the latter 35 s were subjected to the subsequent analysis.

A surface-mounted accelerometer (Crossbow CXL04LP3) was attached to the platform to measure horizontal acceleration of the input exerted on upright standing posture. The accelerometer is a DC accelerometer having a range of ±4G, and can measure not only accelerations caused by force imposed on a segment but also static accelerations such as gravitational acceleration. These characteristics are suitable for postural calculation as a tilt reference. Stretch adhesive bandages were used for the accelerometer to improve the congruence of body motion. An angular rate sensor (Murata ENC-03J) was applied to measure angular velocity of subjects' trunks. The gyroscope has a small, rapid response up to 50 Hz, and a wide range of ±300 deg/sec. This sensor was lightweight and was attached to the trunk area (clavicle) to measure mainly in the sagittal plane and to provide high-resolution measurement of upright stance posture angular velocity.

Each subject underwent horizontal vibration four times individually. For one subject, one more set of data was collected to use for validation. The initial data were preprocessed prior to sampling by a 13 Hz analog low-pass filter. The measured platform acceleration and the trunk angular velocity were sampled at 100 Hz through an A/D converter, and band-pass filtered at 0.2 Hz to 3 Hz by 4th-order Butterworth filter.

2.3 Data Analysis

The coherence function between the input x(t) and the output y(t) of the experimental results is defined by

$$r^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)} \qquad (1)$$

where $G_{xx}(f)$ and $G_{yy}(f)$ denote the autospectral density function of input and output, respectively, and $G_{xy}(f)$ is cross-spectral density function. The coherence function provides a formal measure of the correlation between two signals in the frequency domain. In the ideal case of a constant-parameter linear system with a single clearly defined input and output, the coherence function will be unity. If x(t) and y(t) are completely unrelated, the coherence function will be zero. The coherence function 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 [11]. The coherence function can be interpreted as a measure of linear predictability [12-13] - it equals 1 whenever x(t) is a linear function of y(t), and it is also used in the calculation of 95% confidence limits on the transfer function data [14].

The transfer function (frequency response function) of the system $H(f)$ is then estimated by

$$H(f) = \frac{G_{xy}(f)}{G_{xx}(f)} \qquad (2)$$

The estimated transfer function takes into account the linearly correlated proportion of the output with the input. The transfer function characterizes the dynamic behavior of a system by showing how the output response sensitivity changes as a function of the input. Here for estimating both coherence function and transfer function, a frequency resolution of 0.1 Hz was considered.

The obtained transfer functions for each subject are averaged to represent a unique result with better accuracy than individual results from individual test trials. The adopted averaging method is that of the geometric mean [15-16]. It is defined by

$$\overline{H(f)} = \prod_{k=1}^{n} \sqrt[n]{H_k(f)} \qquad (3)$$

where $H(f)$ indicates the complex form of transfer function for the experiment number k, which is calculated from Eq.(1). The value of n indicates the number of repeated experimental trials. Here the value of n is 4.

It was assumed that the frequency domain noises in the measured signals are normally distributed. It is worthwhile to mention that even the noises of the signals in the time domain are not normally distributed when transferring into the frequency domain; they can be modeled as normal distributed noises [5]. Hence, in this condition, the geometric mean of the transfer functions, obtained from Eq.(3), likely reduces the effects of noise-corruption and give an unbiased estimation of the transfer function better than that of the arithmetic mean.

3. Results

The angular responses of the ankle and hip joint, and the acceleration of platform, were used as the input and output of the postural control system, respectively. The acquired data from the subjects were analyzed in the frequency domain. The correlations between the input and output in the frequency domain, that is, the coherence functions results, are presented in Fig. 3 for the ankle joint and in Fig. 4 for the hip joint. In total, there are four trials per subject, and each individual graph corresponds to a single trial. On average, the coherence results of the ankle joint showed relatively higher coherence than that of the hip joint. Although peak coherence varies across the frequency spectrum, in the majority of comparisons, similar patterns of the coherence plots were found for each subject. The coherence results reveal that the response of the ankle and hip joint showed significant correlations when the subjects were exposed to the translation of the platform.

At frequencies less than 0.5 Hz for both ankle and hip joints, a common fall of the coherences are found. In the frequency ranges above 0.5 Hz, the coherence functions results indicate that the behavior of the system is quasi-linear. In addition, since the experimental data have been averaged across four trials of data (see Fig. 6 and Fig. 7), the amount of noise corruption as well as bias should be approximately lower than each individual data. Therefore, the coherence result may be concluded to be quite satisfactory for estimating the transfer function of the postural control system.

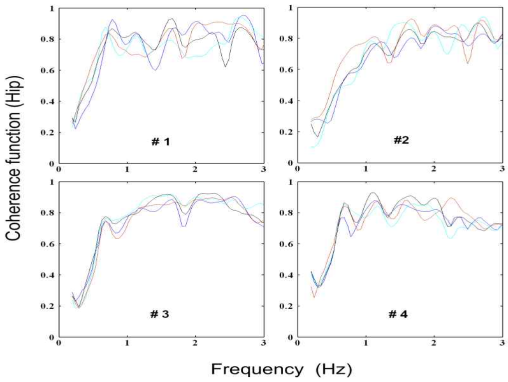

Fig. 3. Coherence functions of ankle from four different subjects (# sign indicates the subject number)

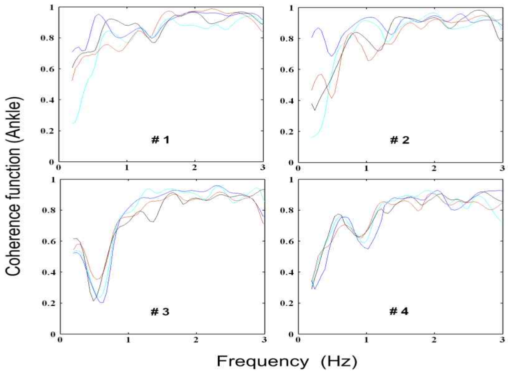

Fig. 4. Coherence functions of hip from four different subjects (# sign indicates the subject number)

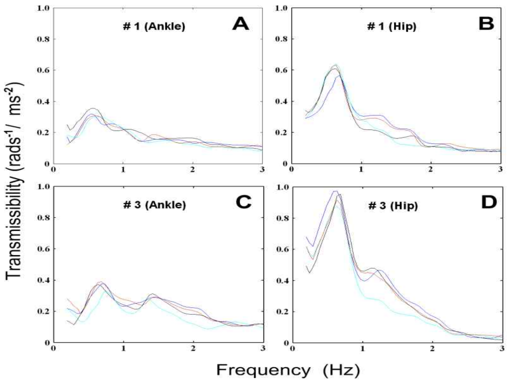

Fig. 5. The transfer functions of ankle and hip joints angular velocities between the platform acceleration(Fig. A, B: subject # 1; Fig. C, D: subject # 3)

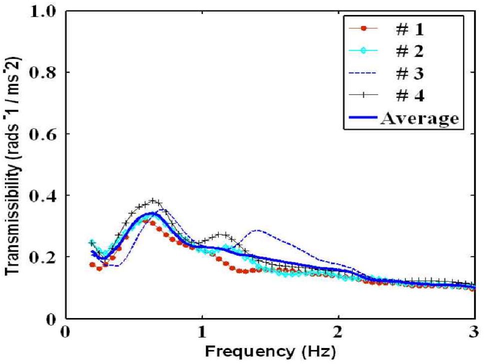

Fig. 6. Geometric mean and average of the ankle transfer functions for four subjects (subjects # 1 to # 4)

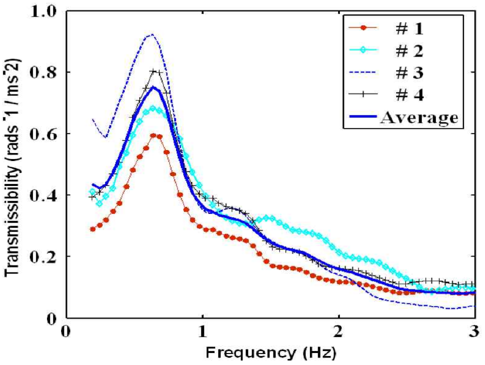

Fig. 7. Geometric mean and average of the hip transfer functions for four subjects (subjects # 1 to # 4)

The frequency response functions, i.e., the transfer functions from two representative subjects between platform acceleration and angular velocities of the ankle and hip joint, are presented in Fig. 5. There are four trials per each ankle and hip joint, and each individual graph corresponds to a single trial of the transmissibility of the postural system, that is, magnitude of the transfer functions. The prominent resonant peaks are observed across all trials, and it is distributed with small deviations within its frequency spectrum and magnitude. This suggests that a high degree of reproducibility exists for the analyzed transmissibility. After the resonant peaks, a significant reduction is found in transmissibility of the postural control system. As a result, it may be concluded that there is a considerable dominant resonance frequency across all estimated data.

The geometric mean from the four trials per subject and its averaged result from across all individual subjects are illustrated in Fig. 6 for the ankle joint and Fig. 7 for the hip joint, respectively. The geometric mean of the transfer functions reveals more clearly one resonant peak. The prominent resonant peaks of the ankle joint were found at 0.58 Hz, 0.63 Hz, 0.7 Hz, 0.63 Hz, with respect to subject number 1 to 4, and its averaged peak was measured at 0.64 Hz.

The magnitude of the transfer functions of the ankle joint at the dominant resonance frequencies for subjects number 1 to 4 are 0.32, 0.34, 0.35, 0.38 rad^{-1}/ms^{-2}, respectively. Interestingly, except for the first subject, the second resonant peaks of the ankle joint were found with its magnitude at 0.23 (1.15 Hz), 0.29(1.4 Hz), 0.28(1.15 Hz) rad^{-1}/ms^{-2} with respect to subjects number 2 to 4. These second resonance frequencies are regarded as the result from ankle and hip strategies when the subjects were exposed to platform translation [1-3]. In the case of the hip joint, prominent resonant peaks were observed at 0.64 Hz, 0.63 Hz, 0.62 Hz, 0.63 Hz, with respect to subject number 1 to 4, and its average was measured at 0.63 Hz. The magnitudes of the prominent resonant peaks were 0.59, 0.68, 0.92, 0.8 rad^{-1}/ms^{-2}, and the averaged value measured as 0.75 rad^{-1}/ms^{-2}.

These results show that Fig. 5 represents the distribution of transfer functions as analyzed from four subjects whose postural control systems were restrained to sway as a two link inverted pendulum.

The significant coherence results in Fig. 3 and Fig. 4 revealed that the phase relationship between the input and output of the postural control system

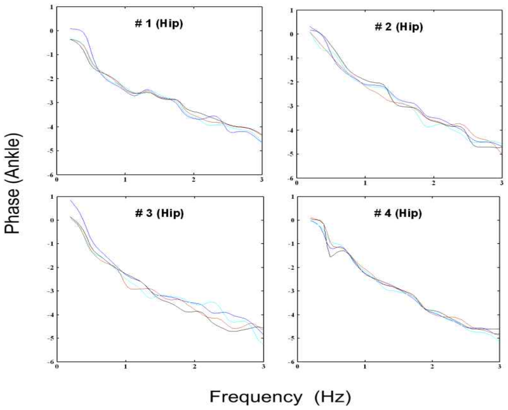

Fig. 8. Phase of the transfer functions for four subjects. Each graph indicates one experiment (Ankle)

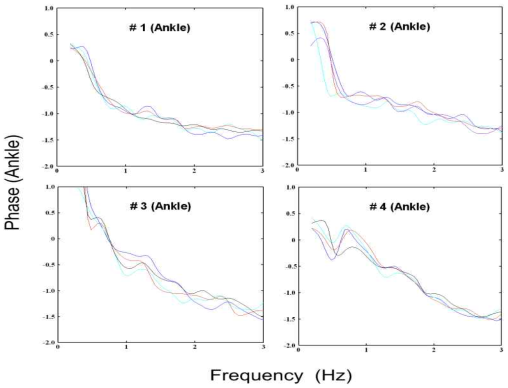

Fig. 9. Phase of the transfer functions for four subjects. Each graph indicates one experiment (Hip)

were relatively constant [11]. The phase results of transfer functions analyzed from four different subjects are illustrated in Fig. 8 for the ankle joint and Fig. 9 for the hip joint, respectively. Each single graph indicates one trial. Around the resonance frequency, the inclination angle of the phase graphs are shown as greater than other frequencies. In addition, almost similar patterns to these results are found across all subjects. This shows that there are significant phase drops at around resonance frequencies, which is in accordance with general characteristics of the phase graphs at resonance frequencies.

4. Discussion

Since this study measures the open-loop responses of the complexity involved in standing posture control systems, Gaussian random vibration are used as the platform input. This type of non-predictive external perturbation can reduce the effects of human voluntary response. The clinical research shows that the contribution of the vestibular and somatosensory reflexes is negligible when the input is a non-predictive random vibration [16].

When a stable human standing body is disturbed abruptly by external perturbation, visual, vestibular, and somatosensory signals are processed by the central nervous system (CNS). These signals are used to select, trigger and control for the purpose what is the most appropriate postural response, so the external perturbations are actively damped, and the perturbation is passively damped by the viscous properties of the musculoskeletal system since it may generate reactionary responses to control standing posture [2, 11-12].

This study hypothesized that the ankle and hip joint rotations of the participants mainly contributed to control their standing postural control. This hypothesis was available from the experimental conditions in which their knee and head were tightly fixed during AP platform translation. The significant coherence results revealed that the hypothesis was reasonable. It suggested that there were considerable correlation responses between the input and output of the system. In other words, when the subject's standing body was exposed at horizontal external perturbation, they can possibly control their standing posture equilibrium through ankle and hip joint responses. The coherence results for each trial were reproducible from trial to trial.

The analyzed data showed that there were relatively lower coherence values at the frequency spectrum between 0.2 to 0.5 Hz. It is reported that this result is mainly due to the active responses by the subject, and it is consistent with a lower signal-to-noise ratio for responses caused by the very low-amplitude stimulus [6, 10]. Besides, the effect of voluntary motion could be improved at a low frequency range. In the frequency range under 0.2 Hz, the active response of closed-loop control from the subject mainly related [13, 14]. Moreover, postural compensation for respiration was reported near 0.2 Hz [15].

In a standing postural control system, if the input perturbation approaches the natural frequency of the subject, the system will reveal a tendency to resonate. The variance of the transfer function estimated at a given frequency band does not decease as the number of trials grows. Instead, the signal-to-noise ratio determines accuracy at each frequency [8]. In this study, the results of transfer function were estimated from the averaged data across all trials; the amount of noise corruption as well as bias should be approximately lower than each individual data. The analysis of the transfer function suggested that there were dominant resonant frequencies. This result is consistent with the assumption that was hypothesized: that the subjects behavior was to sway as a two-link inverted pendulum during the experiment. In addition, each of the responses from the different experimental trials reveals that a similar degree of linearity exists across the overall responses of the subject postural control system.

5. Conclusions

This study intended to measure the open-loop responses of the complexity of the human standing posture dynamics. Significant assumptions were adopted to implement the system. Firstly, posture complexity mainly occurs in the mid-sagittal plane. Secondly, during anterior/posterior (AP) platform translation, the ankle and hip joint rotations of the subject contribute to maintain standing body balance.

The designed experimental condition allowed to proceed this research was: (1) non-predictive random vibration was used as the input of the postural system, (2) the knee and head were tightly fixed when the subject was exposed to the horizontal perturbation.

The significant coherence results revealed that the hypothesis was reasonable. It suggested that considerable correlation responses existed between the input and output of the system, and also proved that the subject can possibly control their standing posture equilibrium through the ankle and hip joint responses.

The frequency response function showed the dominant resonant peaks within its frequency spectrum and magnitude. The analyzed phase results also supported resonance frequencies on the frequency domain estimation. The results of the present study indicate that the subject postural control system was restrained to sway as a two link inverted pendulum. It is consistent with the plan adopted in this research.

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