SUBJECT EXPERIMENTS ABOUT SHAKING RESPONSE OF HUMAN BODY USING EARTHQUAKE EXPERIENCE VEHICLE

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Abstract

The 2011 Tohoku Earthquake extremely affected people and facilities inside the buildings even in Tokyo, which is about 400 km far from hypocenter, although there was no damage in building structures. Since this earthquake, there have been a number of studies on indoor damage assessment during earthquakes, and many studies have been made not only on damage to non-structural materials and furniture fixtures, but also on the effects on people. The contents include evaluating action difficulty and anxiety about shaking, and constructing an earthquake response analysis model for the human body to predict human damage. A vibration model of human body based on inverted pendulum constructed by measuring the floor reaction force of a human standing on the shaking table under a sinusoidal frequency-swept vibration (sweep vibration) test of about 80 cm/s^2 has been proposed, but a large earthquake is outside the scope of this vibration model.

In this paper, we conducted a test of subjects using an earthquake experience vehicle for the purpose of understanding the response of people during a strong earthquake and expanding the applicability of the previous vibration model. The response of each part of the human body was measured by motion capture system. Input motions of the vehicle were sweep vibration and seismic vibration. As a result, it was found that the shaking of each part of the human body is changed by the input frequency of the floor, and that the period in an back and forth direction tends to be longer than that in the right and left direction, and that the difference in vibration mode is observed depending on the direction. The applicability of the previous model by inverted pendulum to this experiment was investigated. In the case of seismic vibration, the simulation results of the human body were able to reproduce the experimental results with some accuracy. Motion capture system revealed that the movement of the limbs controlled the body vibration against the shaking for some experimental cases. The purpose of this study is to show human behavior during earthquakes by using the human response analysis model and to evaluate the seismic performance of buildings in the aspect of human safety.

Keywords: Subject Experiments; Human Body; Earthquake Experience Vehicle

1. Introduction

The 2011 Tohoku Earthquake extremely affected people and facilities inside the buildings even in Tokyo, which is about 400 km far from hypocenter, although there was no damage in building structures. Since this earthquake, there have been a number of studies on indoor damage assessment during earthquakes, and many studies have been made not only on damage to non-structural materials and furniture fixtures, but also on the effects on people. There have been many researches on the quantification of the degree of human anxiety and the degree of behavioural difficulty by the subject experiment using a shaking table [1]. Questionnaire surveys regarding the Great East Japan Earthquake have provided valuable information on indoor damage and effect on human [2]. As for the human damage prediction, it is carried out in the damage assumption by the country and local governments. Human damage is predicted by macro evaluation using the seismic strength and building damage rate from the survey results of past large earthquakes [3]. Performance Assessment Calculation Tool (PACT) has been published by FEMA as seismic performance assessment tool for individual buildings, but loss evaluation is performed by the fragility curve [4]. Some studies have also been proposed for constructing a human body model and assessing human loss directly from the building response [5, 6].

Yamamoto et al. proposed a toppling limit of human body against floor vibration by using a simple vibration analysis model of the standing human body in the left and right directions [7]. A vibration model of human body based on inverted pendulum was constructed by an experiment by sine wave sweep vibration of up to 0.8 m/s^2 in one horizontal direction and two horizontal directions [8], but a large earthquake is outside the scope of this vibration model. And the measurement item related to the human response was only the floor reaction force by the subject's response. In this paper, we conducted a test of subjects using an earthquake experience vehicle for the purpose of understanding the response of human during a strong earthquake and expanding the applicability of the previous vibration model.

2. Outline of experiment

2.1 Earthquake Experience Vehicle

Table 1 shows the specifications of earthquake experience vehicles used in this study. During normal times, it is operated as a facility where you can experience the difference between seismic structure and seismic isolation structure for disaster prevention awareness. Basic input motions are sine wave vibration equivalent to seismic intensity of 1-7 and floor responses of a building against observation record of the Hyogo Prefecture southern earthquake, the Tohoku Pacific Ocean earthquake, and the 2016 Kumamoto earthquake. These earthquake responses are equivalent to the seismic intensity 7 and maximum acceleration of 1,500 cm/s^2.

Table 1 – Specification of earthquake experience vehicles

Experience room	Capacity: 4 people Size: 2,720 mm×1,750 mm×Height 1,830 mm
Actuator	Servo motor
Operating range	Back and forth: ±150 mm Right and left: ±100 mm Up and down: ±25 mm
Maximum speed	600 mm/s
Maximum acceleration	1.5 G

2.2 Input Waves

In this study, the sweep vibration was mainly performed with reference to the previous study [8] to calculate the period of the human body to modify the vibration analysis model. In order to examine the applicability of the vibration analysis model to the shaking of an earthquake, the vibration test by simulated ground motion was also carried out. In addition, white noise waves and sine waves used in previous experiments [1] were adopted. Table 2 shows an overview of the input waves, and Figure 1 shows some examples of waveforms. The X, Y, Z directions in Table 2 are shown in Figure 1. The sweep waves were carried out in two levels, the equivalent of the existing model (0.8 m/s^2) and the maximum amplitude that can be reproduced in the experience vehicle. The seismic waves were also input in two levels: the maximum applicable amplitude by the experience vehicle and half of that. Vibration case is 30 cases per person, it is 30 seconds per case except sine waves 3 and 6. One-directional vibration is excited only in the longitudinal direction of the experience vehicle. The orientation of the subject was changed as in the back and forth, left and right and 45 degrees direction of the subject. The orientation of the subject is in the U, V, W directions as shown in Figure 1. This is because we thought that the experiment should be conducted without the subjects seeing the displacement of the experience room. Sweep vibration is basically changed from high to low frequencies. In the case of two-directional simultaneous vibration, the frequencies change from high to low in the left and right direction of the human, from low to high in the back and forth direction. The input at the time of simultaneous vibration in two-directions was reduced to $1/\sqrt{2}$ times in order to be equivalent to the same input as the one-direction vibration.

Table 2 – Input waves

Frequency or Content	**Direction**	**Level**	**Number of case**
Sweep1: 5-10 sec.	back and forth (X) 45 degree	2 levels: 0.12, 0.2 m/s^2	6
	simultaneous two-axis (XY)	2 levels: 0.08, 0.14 m/s^2	
Sweep2: 2Hz-5 sec.	left and right (Y) 45 degree	2 levels: 0.8, 3.0 m/s^2	6
	simultaneous two-axis (XY)	2 levels: 0.6, 2.1 m/s^2	
Sweep3: 5Hz-3 sec.	back and forth (X) left and right (Y) 45 degree	2 levels: 0.8, 2.7 m/s^2	8
	simultaneous two-axis (XY)	2 levels: 0.6, 1.9 m/s^2	
White noise	back and forth (X) left and right (Y) simultaneous three-axis (XYZ)	1 level: 1.0 m/s^2	3
Earthquake1: Random phase Earthquake2: Kobe phase	simultaneous three-axis (XYZ)	2 levels: 0.7, 1.5m/s^2	4
Sine wave1: 3sec.	back and forth (X) left and right (Y)	1 level: 0.7 m/s^2	2*
Sine wave2: 1.6 sec.	back and forth (X) left and right (Y)	1 level: 2.3 m/s^2	2*
Sine wave3: 0.5 sec.	back and forth (X) left and right (Y)	1 level: 3.0 m/s^2	2*
Sine wave4: 3+4.5 sec.	simultaneous two-axis (XY)	1 level: 0.14+0.5 m/s^2	1*
Sine wave5: 1.6+2.4 sec.	simultaneous two-axis (XY)	1 level: 0.5+1.6 m/s^2	1*
Sine wave6: 0.5+0.75 sec.	simultaneous two-axis (XY)	1 level: 0.6+2.1 m/s^2	1*

* Select 3 cases per person, out of a total of 9 cases.

Results of hatched cases were not used in this paper.

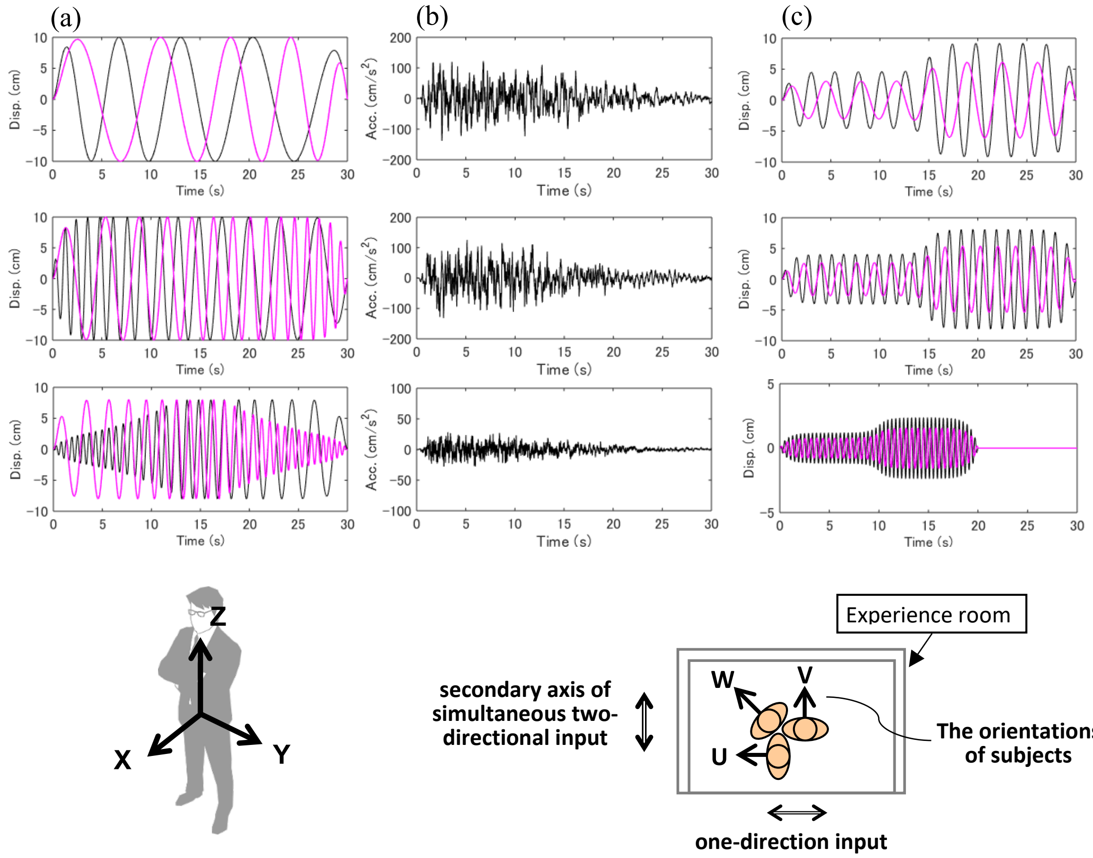


Fig. 1 – Examples of time histories of input waves: (a) Sweep waves (black : one-direction input, pink : secondary axis of simultaneous two-directional input), (b) Seismic waves (Earthquake1), (c) Sine waves (black : one-direction input, pink : secondary axis of simultaneous two-directional input)

2.3 Measurement plan

The movement of the subject was measured displacement of each part of the human body by optical motion capture system [9]. Marker installation position is 18 locations shown in Figure 2. Ten measuring cameras were used, and all of them were installed in the experience room of the earthquake experience vehicle. Displacement of each part of the human body is a relative displacement to the experience vehicle. As for the displacement of experience room of the earthquake experience vehicle, we need fixed points in the sight of motion cameras. Hence, the fixed points were installed in the experience room by extending a boom arm of lighting stand from the ground. The photo at the time of the experiment is shown in Photo1. The portable force plate (for walking/balance analysis, 50cm x 60cm x 5cm [10]) was installed on the floor of the experience room to measure floor reaction force of the subject. Moment and COP (center of pressure) were calculated from the floor reaction force. The accelerometers were installed on the force plate to measure the acceleration input to the subject. As for human motor physiology, wearable biosensor [11] were mounted on the subjects, and the cardiac potential, body surface temperature, respiratory rate, etc. were measured. Not only during the vibration experiment, was it also measured at sleep state the day before and normal and resting times. However, the analysis of physiological data is not reported in this paper. After each vibration, we interviewed to the subjects four items; Physical-1 (dizzy, motion sickness), Physical-2 (pain of back and shoulder, etc.), Psychological (anxiety), Limit (discomfort), and the numbers from 1 to 6 were answered by the subjects. If the answer more than 4 is obtained, the experiment was suspended.

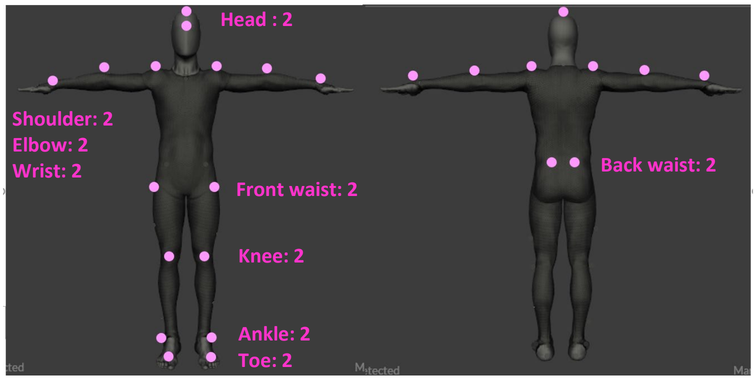


Fig. 2 – Location of Markers (18 points)

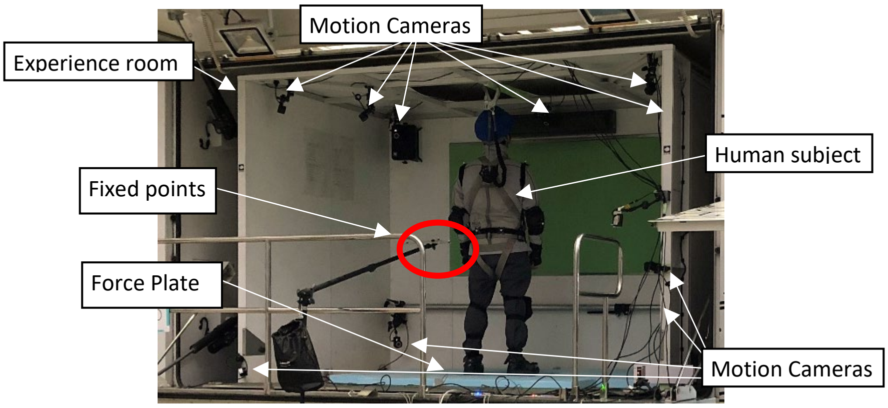


Photo 1- The subject experiment

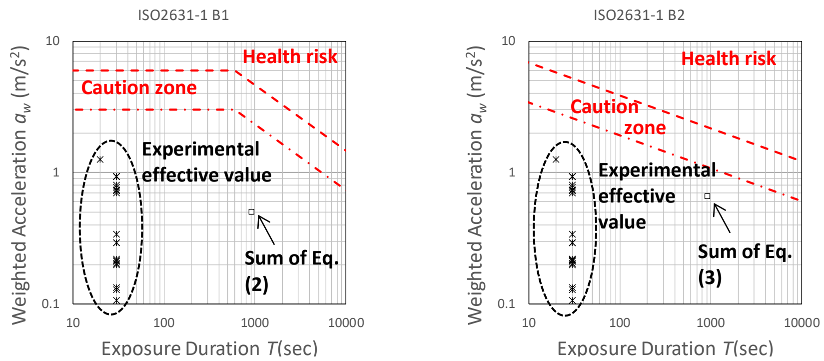
2.4 Subject condition

Two men and two women in their 20s and 50s who are 170 cm or less in height capable of this measurement in the experience room were participated in this experiment. At the time of experiment, wearing a helmet and a full harness, with a biological sensor and markers, on the force plate installed on the floor of earthquake experience room, subjects were exposed to vibrations. Basically, subjects maintain a standing state, but the safety of the subject is the top priority, and when it is likely to lose balance, it was told to prepare for the shaking in the posture that can start stepping immediately. This experiment was carried out with the approval of the ethic examination of Research Institute of Human Engineering for Quality Life.

3. Result of experiment

3.1 Evaluation of human exposure to whole-body vibration

The results of evaluating the effect on the health of the whole body vibration exposure of ISO2631-1 from the acceleration of the force plate are shown in Figure 3. In ISO2631-1, the effect on health risk is evaluated by the magnitude of the effective value by the root-mean-square of the frequency-weighted acceleration [12]. The caution zone is a value of 1/2 of the health risk, which indicates that it is proportional to the square and the 1/4 square root of the duration T. The effective value of each vibration of the experimental results did not reach the caution zone. In addition, the result of the effective value added together in consideration of the duration of all vibrations has not reached the caution zone as well.



$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}} \quad (1) \qquad a_{w,e} = \left[\frac{\sum a_{wi}^2 \cdot T_i}{\sum T_i}\right]^{\frac{1}{2}} \quad (2)$$

$$a_w^2(t) = a_{wx}^2(t) + a_{wy}^2(t) + a_{wz}^2(t) \qquad a_{w,e} = \left[\frac{\sum a_{wi}^4 \cdot T_i}{\sum T_i}\right]^{\frac{1}{4}} \quad (3)$$

Fig. 3 – Evaluation result vibration exposure ISO2631-1

3.2 The influence of frequency and direction of one-direction input

In the case Sweep waves were input in one-direction of the back and forth or the left and right directions of the human, Figure 4 shows the time history a relative displacement to the floor of the experience room of the waist and head of the subject and the time history of the floor displacement of the experience room. The waist and head begin to shake in almost the same phase, the displacement of the floor shakes in the reverse phase, the peak of vibration of the waist or head appears first, then floor displacement appears. As the period of the floor displacement becomes longer, then the head and waist preceded the peak of the vibration of the floor displacement (the waist is slightly faster than the head). The timing at which the amplitude of the peak is maximized and the state of the change in amplitude depends on the input frequency and the input direction. The amplitude of the head tends to be larger than the waist in the back and forth directions. The difference in the amplitude of the head and waist in the left and right directions was smaller than in the back and forth directions, and the waist was sometimes larger than the head. The time history of a relative displacement to

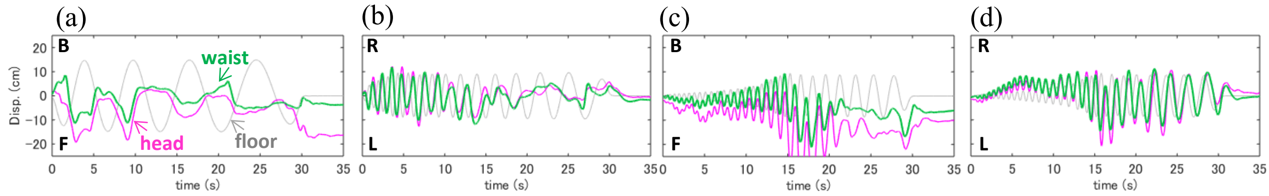


Fig. 4 – The time history results of Sweep wave input: (a) Sweep1 level2 (back and forth), (b) Sweep2 level2 (left and right), (c) Sweep3 level2 (back and forth), (d) Sweep3 level2 (left and right)

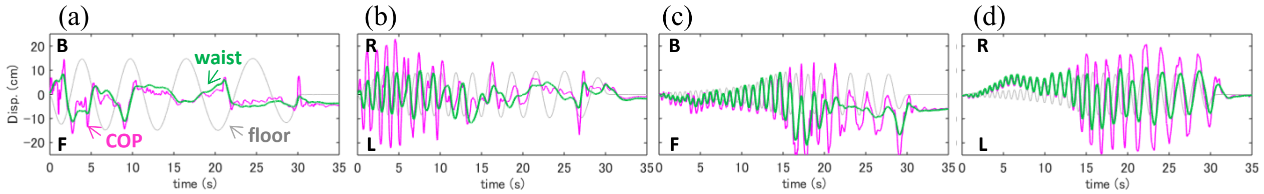


Fig. 5 – The time history results of the Sweep wave input: (a) Sweep1 level2 (back and forth), (b) Sweep2 level2 (left and right), (c) Sweep3 level2 (back and forth), (d) Sweep3 level2 (left and right)

the floor of the experience room of the COP and the waist is shown in Figure 5. Compared to the waist, the amplitude of the COP is large, but tends to move approximately the same phase or a little faster.

3.3 The influence of simultaneous two-directional input

The case inputting Sweep2 level2 input in left and right direction, the case inputting in the 45 degree direction of the subject were compared with the case inputting in two directions simultaneously. Figure 6 shows the time history of displacements of the subject's waist and head and the floor. For the case of inputting in the 45-degree direction, although the response is smaller than at the time of one-direction input, it was generally the same tendency as the one-direction input. On the other hand, in the case of input in two directions at the same time, the influence of the input of the orthogonal direction appeared in the time history. The foot hardly moved in the case of one-direction input, but in the case of two-directional simultaneous input, it became difficult to maintain a stationary state. Since the back and forth direction input in the two-directional simultaneous input is from low frequency, unlike the one-direction input, the waist and the head started from the movement such as to follow the floor displacement, then they shake in the reverse phase of the floor.

For the result of Sweep2 level2 input, the displacement Fourier spectrum of the head and waist of the subject were compared with the floor in Figure 7. The range indicated by the red dashed line is the input frequency. Peaks can be seen in the left and right direction at around 0.5 to 0.9 Hz and around 0.2 to 0.3 Hz. The back and forth direction also appears to have peaks slightly longer than the left and right directions. The difference in the amplitude of between the head and the waist by input directions can be seen from the displacement Fourier spectrum as well. The peak of the low frequency is increased in the two-directional input.

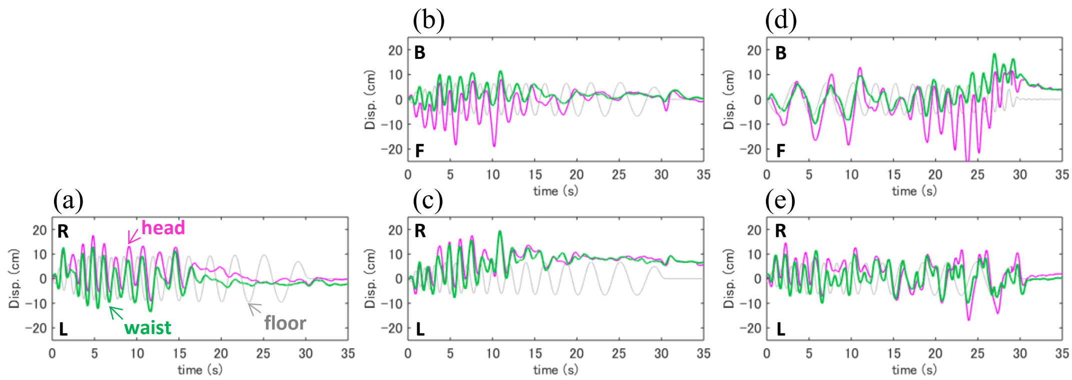


Fig. 6 – The time history results of Sweep2 level2 input: (a) one-direction (left and right), (b) 45 degree (back and forth), (c) 45 degree (left and right), (d) two-directions (back and forth), (e) two-directions (left and right)

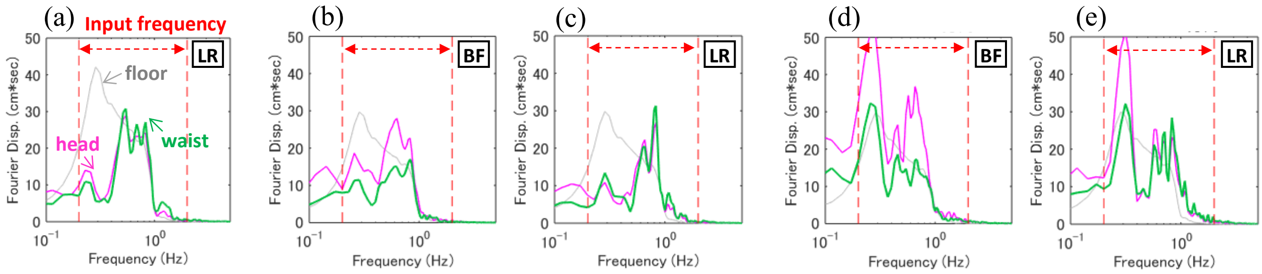


Fig. 7 – The Displacement Fourier Spectrum (pink : head, green: waist, gray: floor):
(a) one-direction (left and right), (b) 45 degree (back and forth), (c) 45 degree (left and right),
(d) two-directions (back and forth), (e) two-directions (left and right)

This seems to be because the subjects lost balance. Although the frequency of the peak varies depending on the subjects, the tendency to appear due to each direction and two-directional simultaneous input was similar regardless of the subjects.

3.3 The differences among subjects

Figure 8 shows the differences in response by the subject for the case of Sweep2 level1 simultaneous two-directional input. Although the response in the back and forth direction is almost the same among all subjects, the responses in the left and right direction of subject A and B change from high to low frequency, and the responses of subject C and D change from high frequency to low frequency, and then change to high frequency again. It seems to be affected by the orthogonal input.

Figure 9 shows the response of the head, waist, knee, and toe in the case Sweep2 level1 in simultaneous two-directional input in the height direction. The gray lines are the superposition of the response for the entire time, and the black line indicates approximately the maximum response. The left side of each graph shows the responses of the back and forth direction, and the right side shows that of the left and right directions. In the back and forth direction, the amplitude of the waist is smaller than the head, and it was observed to vibrate in

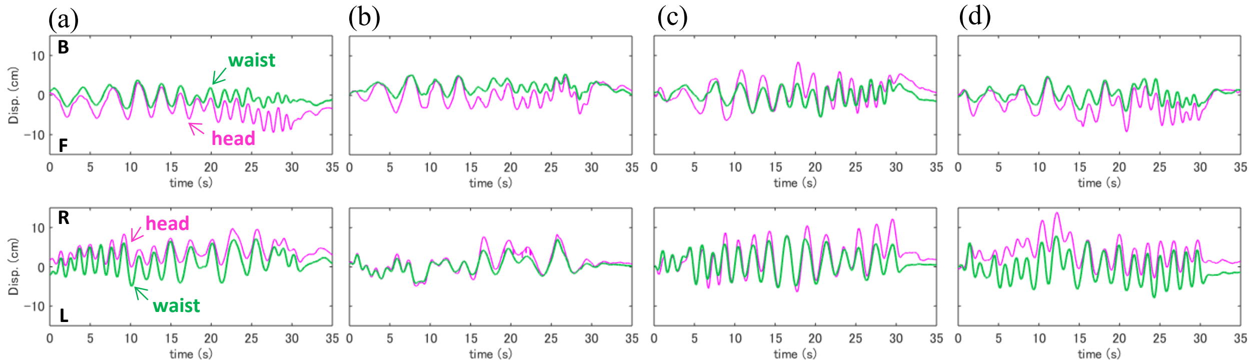


Fig. 8 – The time history results of Sweep2 level1 simultaneous two-directional input (top: back and forth, bottom: left and right) :(a) Subject A, (b) Subject B, (c) Subject C, (d) Subject D

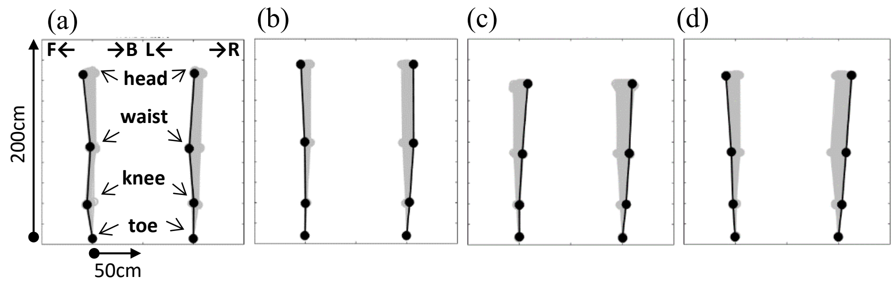


Fig. 9 – Displacement distribution in the height direction of Sweep2 level1 simultaneous two-directional input (left: back and forth, right: left and right): (a) Subject A, (b) Subject B, (c) Subject C, (d) Subject D

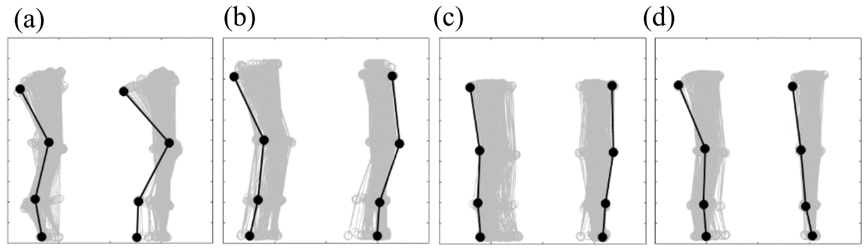


Fig. 10 – Displacement distribution in the height direction of Sweep2 level2 simultaneous two-directional input (left: back and forth, right: left and right): (a) Subject A, (b) Subject B, (c) Subject C, (d) Subject D

the primary mode. In the left and right direction, the amplitude of the waist was about the same as the head, it was sometimes larger. Figure 10 shows the human response in the height direction in the case Sweep2 level2 in simultaneous two-directional input. All of the subjects lost their balance and the movement of the feet was seen to correspond to the shaking. The way to react to the shaking was different by subjects, such as knee flexion, arm movement absorption of shaking, and feet moving.

We confirmed the applicability of the previous model [5] of the left and right directions. The human body model is shown in Figure 10. In which, *P* represents a pin, a thick line indicates a rigid bar. *H* is height, *M* is the mass of the whole body. The rotational stiffness *K* and the rotational damping coefficient *C* were given in the following equations (4) and (5). In the below equations, ω(=2πf) and *h* are the natural circular frequency and damping ratio of the one degree of freedom model. For Subjects A and C, we conducted simulations using the values of the Table 3.

$$K = \{M \times (0.562H)^2 + 0.0524MH^2\}\omega^2 = 0.368MH^2\omega^2 \quad (4)$$

$$C = 2 \times h \times 0.368MH^2\omega = 0.736MH^2h\omega \quad (5)$$

Table 3 - Frequency and damping

	Frequency (Hz)	Damping
Subject A	0.4	0.35
Subject C	0.55	0.20

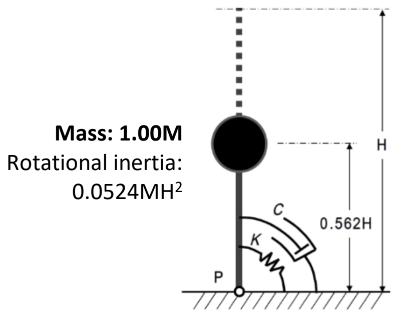


Fig. 10– Previous model

Figure 11 shows the displacement of the center of gravity position of the model comparing with measured displacement at the waist. As for the response at the one-direction sweep input, the experimental results of Subject A decreased after 10 seconds of input, but the simulation results remain large. The reason for this small response in the experiment is thought to be that, humans can predict the movement of the floor and control the body in response to the shaking of the floor. In two-directional simultaneous input, by the influence of the orthogonal direction the difference in the second half of the response is increased. The seismic response of the three-axis simultaneous vibration has been reproduced to some extent, however deviation of the response due to the influence of the orthogonal direction has occurred.

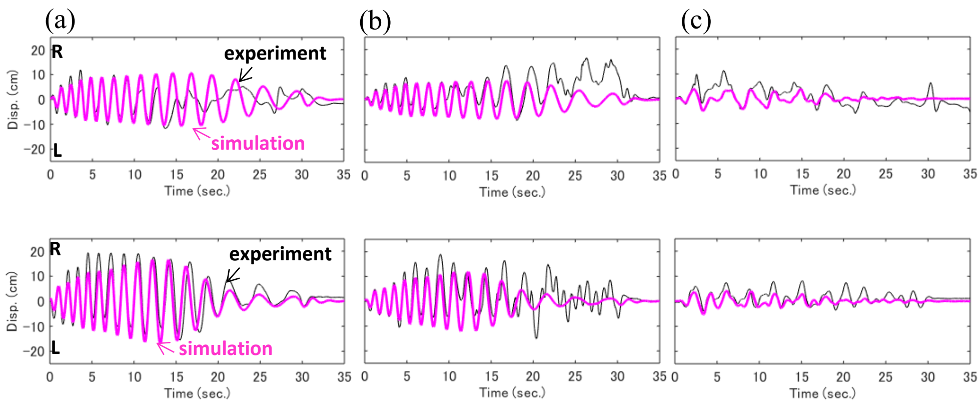


Fig. 11 – The comparison of time history results between experiment and simulation (top: Subject A, bottom : Subject C) : (a) Sweep2 level2 one-direction input (b) Sweep2 level2 two-directional simultaneous input (c) Earthquake1 level2

For the two-directional simultaneous input of the Sweep2 level2 and the Sweep3 level2 in which the feet moved, comparing the limit toppling moment calculated from the initial position of the two toes with measured moment in the experiment, we investigated the relationship between the moment and the movement of the limbs. Figure 12 shows comparison between simulation and experiment for the time history of the displacement of the waist and the time history of the moment of the subjects. Figure 13 shows the displacement amount from the initial position of both wrists and toes. When the measured moment exceeds the limit toppling moment, it can be seen that the left and right differences appear in the movement of the wrist, and the foot is moving. However, the simulation has not reproduced instantaneous changes.

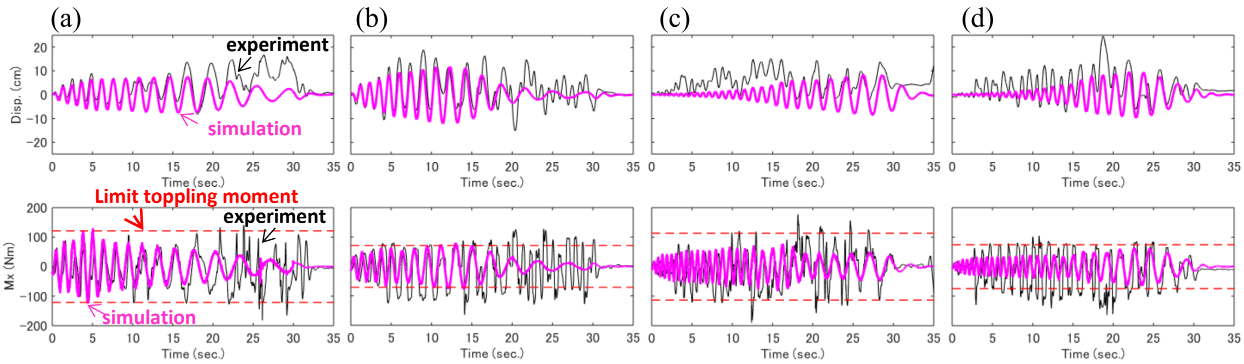


Fig. 12 – The comparison of time history results between experiment and simulation of Sweep simultaneous two-directional input (top: displacement of waist, bottom : moment) : (a) Subject A Sweep2 level2, (b) Subject C Sweep2 level2, (c) Subject A Sweep3 level2, (d) Subject C Sweep3 level2

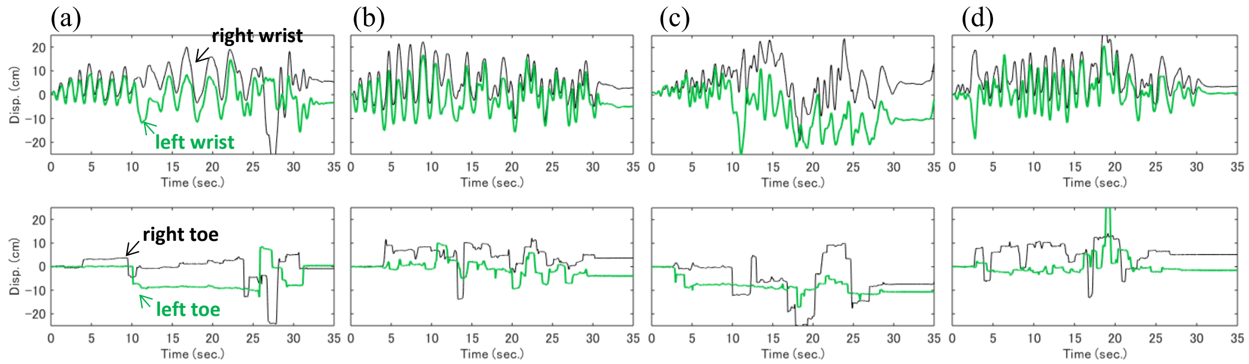


Fig. 13 – The displacement time history of Sweep wave simultaneous two-directional input (top: displacement of wrists, bottom : displacement of toes) : (a) Subject A Sweep2 level2, (b) Subject C Sweep2 level2, (c) Subject A Sweep3 level2, (d) Subject C Sweep3 level2

4. Conclusion

In order to understand the vibration characteristics of the human body, the subject experiment using earthquake experience vehicle was conducted. The response of each part of the human body was measured by motion capture, and the response of sweep vibration was mainly discussed. It was found that the mode characteristics differs in the left and right direction of the human and the back and forth direction, and that the input in the orthogonal direction affects the response of subjects simultaneous two-directional input. The applicability of the previous model was examined. For the sweep wave, the analysis was larger than the experiment in the one-direction input. Although the trend could be reproduced for the response of sweep wave in the two-directional input and the seismic response, the influence of the orthogonal direction need to be considered to construct a human response simulation model including the movement of the limbs. The purpose in future is to show human behavior during earthquakes by using the human response analysis model and to evaluate the seismic performance of buildings.

5. Acknowledgements

We would like express our thanks to Bridgestone Co., Ltd. for the great cooperation regarding the use of earthquake experience vehicle.

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