基礎論文 Paper

Immersive Walking Environment for Analyzing Gaze-gait Relations

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Abstract – We analyzed changes in human gait (way of walking) that corresponded to changes in human gaze direction. For the purpose, we constructed an immersive walking environment in which we measured participant gait in various controlled gazing situations via a motion capture system and an eye tracker. The environment consisted of a treadmill and 180-degree multi-screen for presenting the gazing target. As preliminary analysis of gaze-gait relations, in this paper, we focused on arm and leg swing amplitudes as a measure of gait and analyzed the relationship between gaze and arm/leg swings. Unlike previous studies, we sought to analyze behavior that occurred when humans intentionally gazed at a specific target. Our experimental results indicate that arm swing is affected by gaze direction. We observed a tendency for decreased swing amplitude in the arm further from the gazing direction, and for increased swing amplitude in the arm closer to the gaze direction. Contrary to our results for arm swing, we did not observe any evidence of modulated leg motion by gaze direction. Our results suggest that it may be possible to estimate gaze from human gait.

Keywords : Gait analysis, Gaze direction, Motion capture, Eye tracking, Treadmill, Arm and leg swings

1 Introduction

We make both head and eye movements to obtain visual information about the world around us [2, 18]. Many researchers have reported the relationships between eye and head movements [4, 5, 13, 17, 19]. To obtain a wider range of visual information, an individual may tend to move not only their eyes and head but also their chest (trunk). Thus, several studies have analyzed and described relationships among eye, head, and chest movements [1, 16]. These studies demonstrated cooperative movements of the eyes, head, and chest when people change the direction of their gaze.

During walking, the eyes, head, and chest also move in a cooperative way to stabilize gaze direction. Many studies have focused on compensatory movements of the eyes, head, and chest during different walking conditions [6, 7, 8, 9, 11]. These investigations have shown that the eyes and head move cooperatively when individuals walk in a straight line [9], in circles [6], turn to change direction [7, 8], and on a treadmill [11].

In those researches, the participants were instructed to just walk in designated trajectories and not instructed to gaze at something. Thus, those researches did not focus on behavior that occurred when humans intentionally gazed at a specific target. Unlike the previous studies, we aim to analyze such intentional gaze behaviors. For the purpose, we need to present gaze target to participants who are walking in various directions, and capture the participants movements precisely for long periods. To obtain such observations, we create an immersive walking environment which consisted of multiple screens, projectors, a treadmill, and measurement devices (motion capture and eye tracking systems). These structures enable us to show not only gaze target but also surrounding environments and create a sense of immersion in the environment for the participants. Further, we can capture the participants' whole body movements including gaze for long durations.

In addition, as preliminary analysis of gaze-gait relations using our immersive environment, we analyzed arm and leg movements in controlled gazing conditions. Specifically, we used motion capture and eye tracking systems to capture changes in human

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gait that corresponded to gaze direction.

In the next section, we describe related researches. In Section 3 we describe the immersive walking environment and its calibration, and show its evaluation. In Section 4 we show our analysis results of arm and leg movements, and discuss our findings. Section 5 concludes this paper.

2 Related researches

Many researchres have analyzed and reported the relations among the eyes, head and chest movement during walking [6, 7, 8, 9, 11]. These reseaches did not aim to analyze behaviors that occurred when humans intentionally gazed at speciifc targets. Thus, there were no apparatus for presenting the gazing targets in their experimental environment. Cinelli et al. [3] analyzed the relations of the eyes, head and chest while the participants were gazing at targets during walking. However, their environment consisted of just multiple LEDs, they showed only the gazing targets and could not show the surrounding environment such as corridor.

Reed-Jones et al. conducted experiment in VR environtments and measured whole-body movements caused by viewing VR scenes [14, 15]. In their experiment, the participants watched moving scenes that simulates walking towards and turning a corner. They showed that the participants behaviors were similar to those observed during real turning. Their results suggest that presenting surrounding environment are important for analyzing gaze-gait relations.

Some researchers analyzed the relationship between human gait and gaze direction [10, 12]. Mitsugami et al. measured the movement of various human body parts, such as arms and legs, in natural walking situations and reported that arm swings are affected by gaze direction [10]. Nakazawa et al. reported that gait is affected by head orientation and proposed a method for estimating head direction via gait observation [12].

In this study, we precisely analyzed arm and leg movements in controlled gazing conditions. Specifically, we used motion capture and eye tracking systems in immersive walking environments to capture changes in human gait that corresponded to gaze direction. We created an experimental immersive walking environment, which enable us to precisely examine gaze target in specified directions.

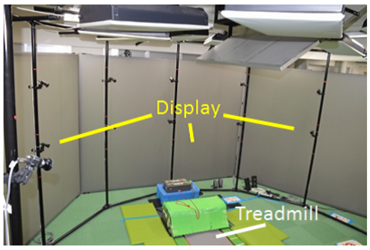

図 1 Immersive walking environment

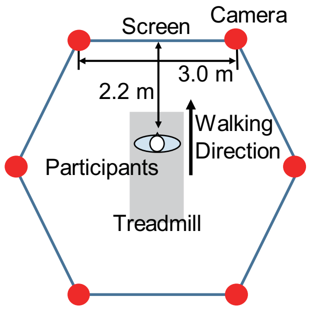

図 2 System configuration

3 Immersive walking environment

3.1 System requirements

In our research, we aim to analyze gaze-gait relations. For the purpose, as described in Section 1, we need to show gaze target to participants who are walking in various directions, and also capture the participants movements precisely for long durations. We summarize the requirements for our experimental environment as follows:

1. The participants can walk naturally.
2. The gaze target can be presented in the designated directions to the participants for long durations. Further, the target can be shown as if it would actually exist in the world the participant are walking in.
3. Whole body movements and gaze behaviors can be measured in the common coordinate system.

3.2 System configuration

Figure 1 shows our experimental immersive walking environment, which consisted mainly of multiple screens, projectors, a treadmill, a motion capture system and a wearable eye tracker (Figure 2). These devices are divided into two parts: displaying devices for showing virtual environment, and measuring devices for capturing gaze direction and whole body movements. This configuration enabled us to analyze gaze-gait relations.

図 3 Scene of participant viewpoint

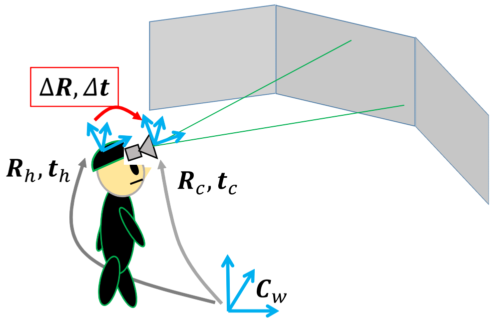

図 4 Relations among devices

3.3 Displaying devices

To show various gaze targets in various directions and positions to the participants and create a sense of immersion in the environment for the participants, we use multiple screens, projectors, a treadmill and a rotary encoder. The speed of the treadmill is controllable. However, it does not run correctly at the specified speed due to variation of walking style and weight of a walking person. Our system is thus equipped with a rotary encoder to obtain its actual speed. The optical rotary encoder is consisted of two fiber optic sensors (Keyence FU-67), and attached it to the treadmill. This rotary encoder enabled us to show scenes of virtual space corresponding to the participants' actual walking speed. In addition, we displayed a corridor-like virtual space. The corridor had brick-like texture in order to make participants feel a sense of speed intuitively. These configuration enable us to create a sense of immersion in the environment for the participants. Figure 3 shows an example image from participant viewpoint. We can display scenes of the virtual space on the immersive walking environment using the multiple screens.

3.4 Measuring devices

3.4.1 Overview

For measuring gaze-gait relations, we installed a motion capture system and a wearable eye tracker. The motion capture included six cameras (Bonita 10, Vicon Motion Systems Ltd., UK) that were located around the experimental environment (Figure 2). Using the motion capture, we were able to obtain information about all body positions and poses. Gaze direction was measured using a wearable eye tracker (EMR-9, NAC Image Technology Inc., Tokyo, Japan). The eye tracker is consisted of two eye cameras for observing eyes and one view camera for capturing the participants view images. The outputs of the eye tracker are 2D positions in the view camera images.

To analyze the relationship between gait and gaze, it was necessary to obtain both pieces of data in a fixed common coordinate system. Thus, we needed to assess the relationship between the view camera of the eye tracker and the motion capture system in advance. This enabled us to convert the two-dimensional (2D) gaze information to three-dimensional (3D) gazing directions.

3.4.2 Calibration

Figure 4 shows the relationship between the motion capture and eye tracker systems. To properly integrate the gaze and gait data, we needed the poses and positions of the view camera of the eye tracker $\mathbf{R}_c^{(t)}, \mathbf{t}_c^{(t)}$ in world coordinates $\mathbf{C}_w$ at time t during the experiments. However, it is difficult to accurately estimate $\mathbf{R}_c^{(t)}, \mathbf{t}_c^{(t)}$ using only the view camera observations. Here, since the view camera of the eye tracker was mounted on the head of each participant, $\mathbf{R}_c^{(t)}, \mathbf{t}_c^{(t)}$ of the view cameras changed in conjunction with the pose and position of the participant' head, $\mathbf{R}_h^{(t)}, \mathbf{t}_h^{(t)}$, and $\mathbf{R}_h^{(t)}, \mathbf{t}_h^{(t)}$ could be measured by the motion capture system. If the relative relationships $\Delta\mathbf{R}$ and $\Delta\mathbf{t}$ between $\mathbf{R}_c^{(t)}, \mathbf{t}_c^{(t)}$ and $\mathbf{R}_h^{(t)}, \mathbf{t}_h^{(t)}$ are known, $\mathbf{R}_c^{(t)}, \mathbf{t}_c^{(t)}$ can be calculated as follows:

$$\mathbf{R}_c^{(t)} = \Delta\mathbf{R}\mathbf{R}_h^{(t)} \quad (1)$$

$$\mathbf{t}_c^{(t)} = \mathbf{R}_c^{(t)}(\mathbf{R}_h^{(t)})^{-1}\mathbf{t}_h^{(t)} + \Delta\mathbf{t} \quad (2)$$

To estimate $\Delta\mathbf{R}$ and $\Delta\mathbf{t}$, a chessboard is first displayed on the screens and more than three images are captured by the view camera of the eye tracker. The poses and positions of the view camera, $\mathbf{R}_c^{(t)}$ and $\mathbf{t}_c^{(t)}$, and intrinsic parameters of the view camera, $\mathbf{A}$, can be estimated from these observations. At the same time, the poses and positions of the participant's head are acquired by the motion capture system at the timings of capturing images by the view camera. With the above information, we were able to

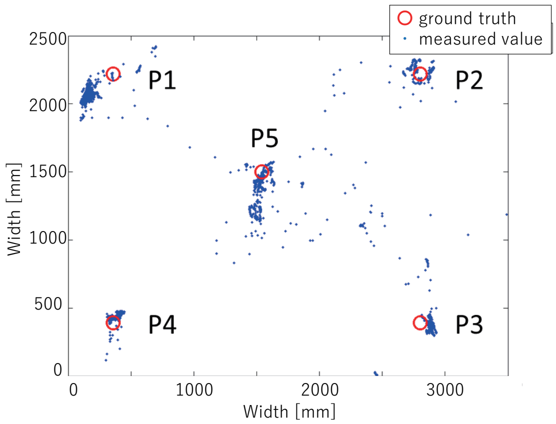

図 5 Estimated gaze positions

表 1 Estimated gaze direction errors [deg]

	P1	P2	P3	P4	P5	Ave.
Horizontal	5.77	3.70	6.53	3.45	3.33	4.71
Vertical	5.92	5.50	1.29	3.52	5.24	4.59

calculate $\Delta\mathbf{R}$ and $\Delta\mathbf{t}$. These calibration steps must be performed in advance of the experiment.

Using the parameters calculated in the calibration step, we were able to convert the 2D gaze information measured by the eye tracker to 3D gaze direction information in world coordinates. Let $\mathbf{p}^{(t)} = [u^{(t)}, v^{(t)}]'$ be the 2D gaze position in the view camera at time t, and $\mathbf{V}^{(t)}$ be the 3D gaze direction in $\mathbf{C}_w$ at time t. These can be calculated as

$$\mathbf{V}^{(t)} = s(\mathbf{R}_c^{(t)})^{-1}\mathbf{A}^{-1}\tilde{\mathbf{p}}^{(t)} \quad (3)$$

where $\tilde{\mathbf{p}}^{(t)} = [u^{(t)}, v^{(t)}, 1]'$ and s is constant.

3.4.3 Evaluation of 3D gaze accuracy

To evaluate the conversion accuracy of our 3D gaze direction data, we performed the following experiment. We displayed the gazing targets in front of the participants who were asked to look at the target. We performed an experiment in which participants looked at fixed targets. Figure 5 shows the gazing positions on the front screen converted from the estimated 3D gaze directions. Here, "∘" denote the ground truth and "·" denote the estimated gaze directions. Table 1 shows the measured error of the 3D gaze directions from the ground truth data. The error values of the 3D gaze directions were less than five degrees.

3.5 Discussion

Our experimental environment consisted mainly of multiple screens, projectors, a treadmill and measurement devices. These configuration enable us to capture gaze directions and whole body movements of participants during walking, In addition, a rotary encoder which can obtain the treadmill actual speed enables us to show scenes of virtual space corresponding to the participants actual walking speed. Thus, the requirements 1 and 2 are satisfied. Furthermore, our immersive environment enables us to analyze conditions and factors that cannot be analyzed in natural walking situations. For example, we can analyze effects of target directions and distances on gait independently; in our environment we can easily change distance of the target while keeping its direction, and change the direction while keeping the distance, which is difficult to realize in the natural situations.

The results in 3.4.3 indicate that the gaze directions by the eye tracker and the body movements by the motion capture can be measured in the common coordinate system, and the requirement 3 is satisfied.

From the above discussion, we confirmed that our proposed environment can satisfy all requirements.

4 Preliminary analysis of gaze-gait relations

In this section, we describe preliminary analysis of gaze-gait relations using our immersive walking environment. Mitsugami's research [10] confirmed that the arm swings were affected by gaze direction in natural walking situation. To confirm the availability of our immersive walking environment, we analyzed arm and leg motions in our environment.

4.1 Experimental setup

In our experiment, we displayed the gazing target as shown in Figure 6. We used a green sphere, 50 cm in diameter, as a gazing target. This was shown on the front screen only, and the scene in the virtual space is shown on the front three screens because of safety concerns.

Before the experiments, the participants walked on the treadmill for five minutes to familiarize themselves with the treadmill. Speed of the treadmill was determined so as that a participant could walk naturally and this speed was used in the experiments. Each participant walked at his/her natural speed. Their speeds ranged from 2.5km/h to 3.0km/h.

Next, we performed experiments as follows: We prepared five directions (Figure 7). In each condition, the gazing target was shown at its designated position for 7.2 seconds. The participants were in-

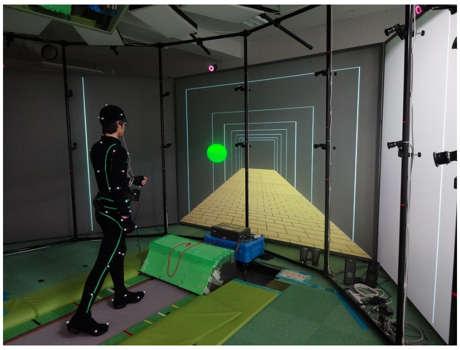

図 6 Experimental environment

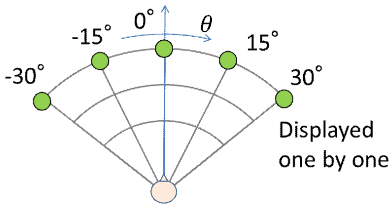

図 7 Experimental conditions

structed to look at the gazing target while walking. The order of the condition was counter-balanced, and the participants took three-minute breaks after walking for five minutes to reduce fatigue.

A total of 14 male participants (A-N), ranging in ages 21 to 24 years, participated in the study. Oral informed consent was obtained from each participants.

4.2 Preprocessing

Before beginning the experiment, we captured their poses of the upper arm, forearm, upper leg, and lower leg. We set the poses as zero when the limb was positioned in a vertically downward position, and the poses become positive when the limbs moved forward as shown in Figure 8.

Figure 10 shows examples of the obtained poses of the upper arm, forearm, upper leg, lower leg, and gaze directions. In the experiment, we projected the gaze target in one direction for 7.2 seconds, after

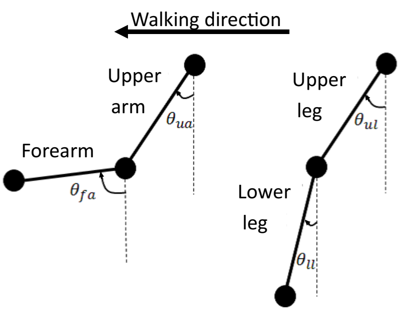

図 8 Definitions of arm and leg poses

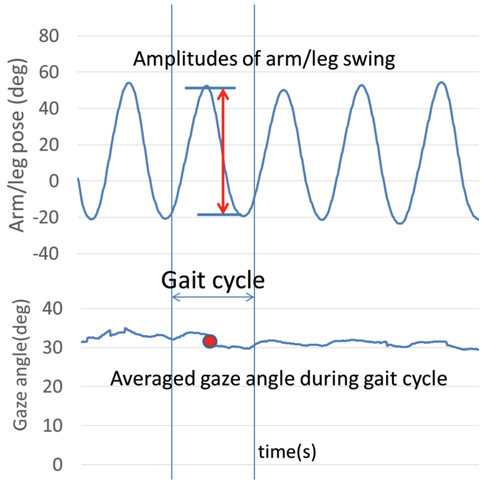

図 9 Feature extraction of arm/leg and gaze

which it disappeared. Then, the target was projected in the next direction. The thick lines in the graphs denote the timings of the target appearances.

When the target position is changed, a participant has to move his/her head and eyes to gaze at the new position. To eliminate periods for it, which we call transition phase, we excluded data collected during a certain time period after the target appeared from the analysis, opting to use only the stable period. From the captured data, we experimentally determined the durations of the excluded periods to be 1 seconds (gray periods in Figure 10). Thus, we used the remaining 6.2 seconds for analysis, and calculated the forearm, upper arm, lower leg and upper leg amplitudes during all gait cycles and averaged the gaze direction for each gait cycle (Figure 9).

4.3 Results

Figures 11-18 show the relationships between the gaze and the amplitudes of the upper arms, forearm, upper leg and lower legs in Participant H, whose results were representative of the participants group. The horizontal axes denote the averaged gazing directions during a gait cycle, and the vertical axes denote the amplitudes during the gait cycle. The lines denote the line fitting results, obtained via robust estimation. Table 2 shows the gradients of the fitted lines of all participants. Red denotes positive values ($\geq \varepsilon$) and blue denotes negative values ($\leq -\varepsilon$). Here, ε is the threshold value calculated from the standard deviations of the swing amplitudes of each part of all participants when the participants gaze at 0 [deg] target. (ε = SD*0.1/30 in this paper. This means the gradient which causes over 10 % of the

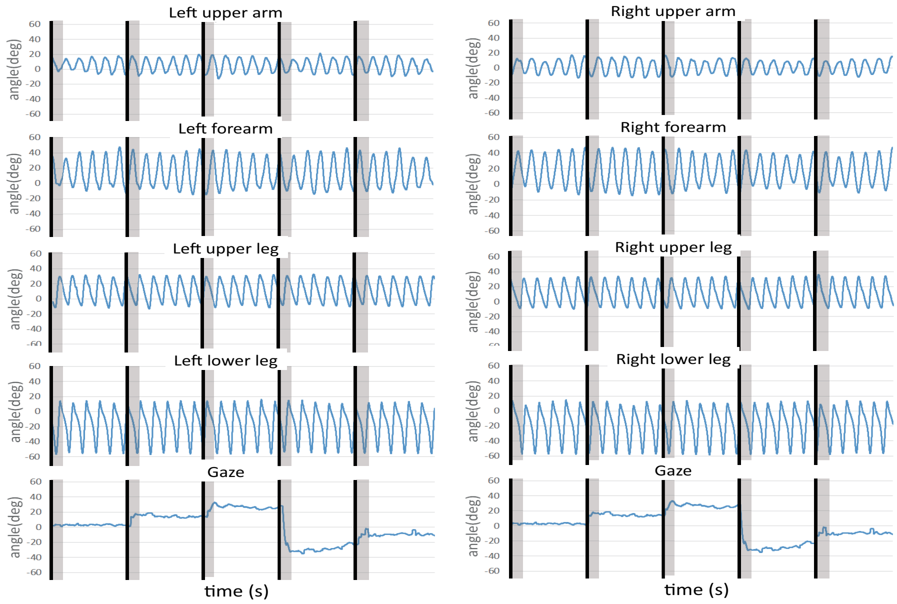

図 10 Example of observations

表 2 Gradients of arms and legs amplitudes

Participant	Upper arm		Forearm		Upper leg		Lower leg	
	Left	Right	Left	Right	Left	Right	Left	Right
A	**-0.014**	0.000	**-0.051**	**0.031**	0.015	**-0.004**	0.010	**0.005**
B	0.034	**0.078**	0.038	**0.112**	0.008	-0.012	0.014	**0.002**
C	0.013	**0.028**	-0.000	**0.075**	0.024	**-0.000**	**0.007**	**0.001**
D	**-0.017**	-0.030	**-0.028**	-0.081	**0.000**	0.022	**-0.000**	**0.006**
E	0.043	**0.106**	0.033	**0.314**	**0.004**	0.027	-0.035	**-0.002**
F	-0.012	**0.023**	0.008	**0.036**	0.015	-0.012	**-0.005**	**0.006**
G	0.006	-0.026	-0.015	-0.002	**0.003**	**-0.001**	0.034	0.026
H	**-0.094**	**0.061**	**-0.121**	**0.182**	**0.006**	0.016	0.058	-0.012
I	**-0.155**	-0.002	**-0.231**	**0.071**	0.059	**-0.004**	0.029	0.056
J	**-0.026**	**0.047**	-0.010	**0.086**	**0.004**	-0.011	**-0.006**	-0.027
K	**-0.050**	-0.037	**-0.158**	-0.112	0.022	-0.010	**0.007**	**0.000**
L	**-0.015**	**0.050**	-0.007	**0.230**	**-0.003**	0.009	0.013	**-0.007**
M	-0.010	-0.002	-0.016	**0.030**	**0.006**	0.014	**0.000**	0.009
N	0.009	**0.060**	0.072	**0.191**	0.027	-0.011	-0.008	-0.026

standard deviation when the participants gaze at 30 [deg] target. 0.013, 0.028, 0.007, 0.009 for upper arm, forearm, upper leg and lower leg). For the arm movement results, many of the participant gradients for the left arm were negative (7/14 for the upper arm and 5/14 for the forearm) and most of the gradients for the right arm were positive (8/14 for the upper arm and 11/14 for the forearm). These results indicate that the amplitude of the arm on opposite side of gaze direction decreased and the amplitude of the arm on the same side of gaze direction increased. The results that show this tendency are shown in bold in Table 2. Similar results can be observed in [10], i.e., they cannot confirm that the gaze directions affect the leg motion. Contrary to the arm results, we did not observe this tendency in the leg results. The leg amplitudes of many of the participants were small (7/14 and 4/14 for the upper legs, and 6/14 and 8/14 for the lower legs, as shown in bold in Table 2). These results indicate that leg motions are less strongly affected by changes in gazing direction.

To summarize the above results, arm swing amplitudes tended to be affected by the gazing direction. In contrast, gazing direction did not affect leg motion.

4.4 Discussion

Our experimental results indicate that the swing amplitudes of the arm further from the gazing directions decreased, and the amplitudes of the arm closer to the gazing direction side increased in response to fixation on the visual target. These tendencies in the arms were similar with the results reported by [10].

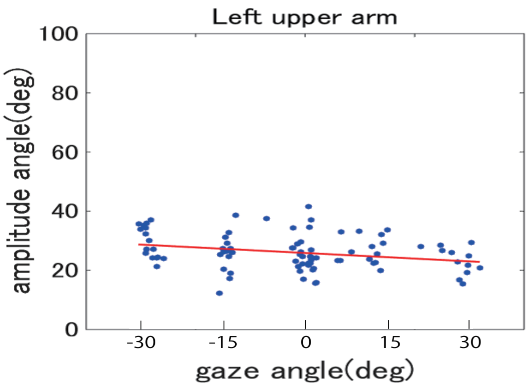

図 11　Amplitudes of left upper arm and gaze (H)

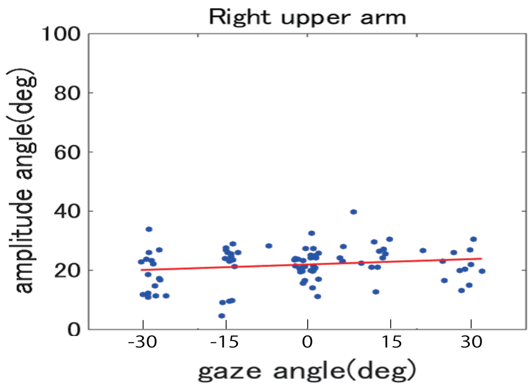

図 12　Amplitudes of right upper arm and gaze (H)

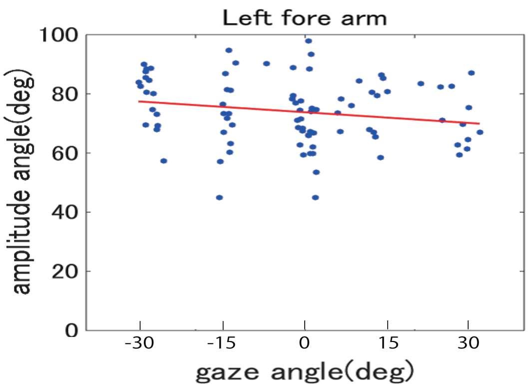

図 13　Amplitudes of left forearm and gaze (H)

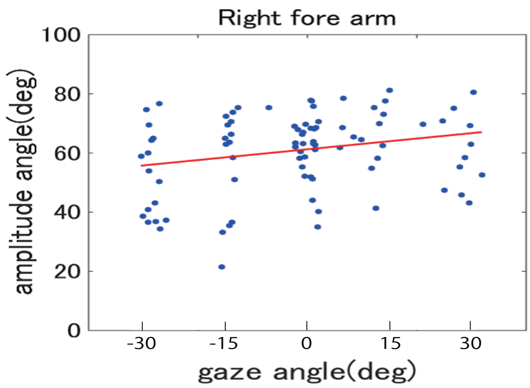

図 14　Amplitudes of right forearm and gaze (H)

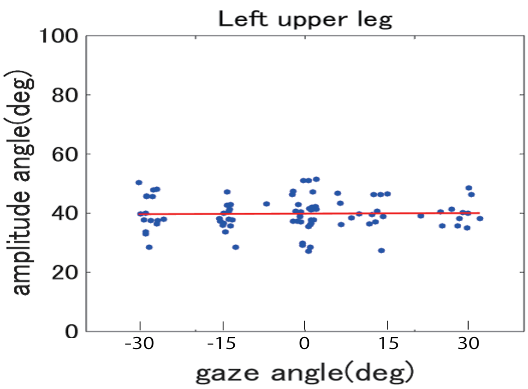

図 15　Amplitudes of left upper leg and gaze (H)

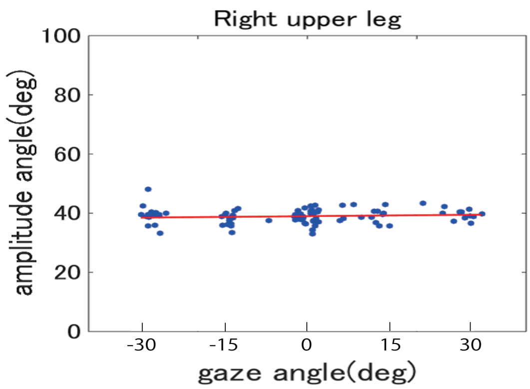

図 16　Amplitudes of right upper leg and gaze (H)

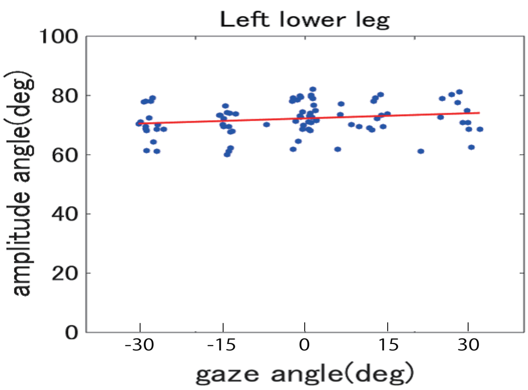

図 17　Amplitudes of left lower leg and gaze (H)

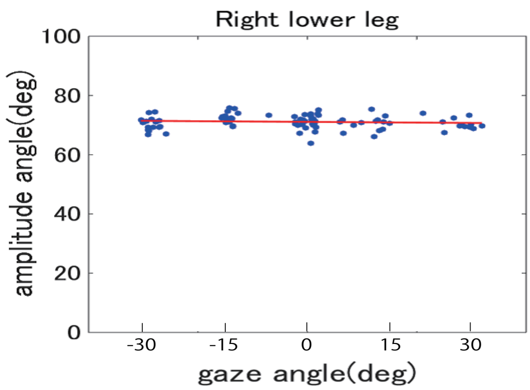

図 18　Amplitudes of right lower leg and gaze (H)

Thus, we confirmed that similar results can be obtained in both our immersive environment and natural walking situations.

In contrast, this did not appear to be the case for leg swing amplitudes. A possible explanation for the different tendencies observed in the arms and legs is that leg motion is directly related to walking behaviors, i.e., leg motion cannot be changed independently from walking speed. Contrary to this, we can move our arms freely while walking. Thus, the relationship with walking behaviors may explain the observed difference between arms and legs.

In addition, although further analysis is required, our data indicates that arm swings amplitude is affected by gazing direction. Thus, this study provedes evidence for the notion of gaze direction estimation based on gait.

5 Conclusion

In this paper, we described our immersive walking environment and our preliminary analysis of gaze-gait relations. We constructed an immersive walking environment that comprised multiple screens and projectors and a treadmill. In this environment, we measured participant gait and gaze via a motion capture system and an eye tracker, respectively. We described the environment and the calibration required to obtain both gait and gaze in common coordinates.

After building the environment, we conducted the preliminary experiment of relations between gaze and gait. We found that arm swing was affected by gaze direction, and we identified a tendency towards decreased/increased swing amplitude in the arm located further/closer to the gazing direction, respectively. Contrary to the arm results, we did not observe similar tendencies in terms of leg motion. Although further analysis is required, we confirmed that gait, specifically arm swing, is affected by gazing direction. Through the experiment, we confirmed that similar results can be observed in both our immersive environment and natural walking situations, although the participants are different.

Future works include further analysis of gaze-gait relations using our immersive environment, such as the use of moving gaze targets. Through analyzing gait-gaze relations using the proposed environment, we aim to achieve gait-based gaze estimation, e.g., gaze estimation by observing arm swings.

Acknowledgments

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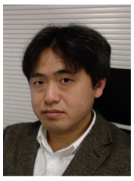

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