Multi-dimensional effects in galvanic vestibular stimulations through multiple current pathways

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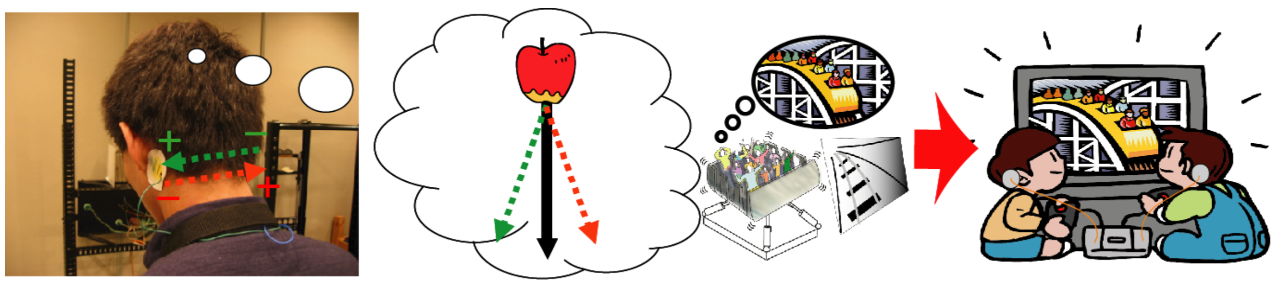

Fig. 1 Galvanic vestibular stimulus (GVS) for equilibrioceptional display

Abstract

This study describes multi-dimensional effects in galvanic vestibular stimulations through multiple current pathways. In this study, we propose a model of three current pathways for GVS. To confirm the presence of the pathways, DC resistances through head were measured in Experiment 1. In Experiment 2, the sway of standing subject was measured as the multi-dimensional effect of GVS through the three pathways. A new yaw rotational sway response was found by the novel method of GVS using four electrodes. The new method is available to realize a multi-dimensional equilibrioceptional display by GVS.

Key words: galvanic vestibular stimulus, anatomical current pathway, sway of standing, equilibrioceptional display

1. Introduction

The inner ear is closely involved in the VR experience, for it provides clues as to posture and motion. Because many VR experiences are designed around the illusion of movement, a conflict will exist between the visual experience and the inner ear experience [1]. In the real world, this conflict is the basic source of motion sickness and loss of balance [2, 3]. Motion sickness is commonly experienced in one form of virtual environment: the flight simulator. Take cabin rides in amusement parks as an example. While the jerking, shunting, and rolling motion of the cabin makes the experience seem much more real than the view from a passive seat at the movies, motion sickness (MS) may arise in viewers from the sensory conflict arising from inadequate visuo-vestibular agreement [4]. It suffices to say that motion sickness has occurred in VR and is a potential problem.

With galvanic vestibular stimulation (GVS), electrical current is delivered transcutaneously to the vestibular afferents through electrodes placed over the mastoid bones. This serves to modulate the continuous firing levels of the vestibular afferents, and causes a standing subject to lean in different directions depending on the polarity of the current. Specifically, anodal and cathodal currents decrease and increase, respectively, the firing rates of vestibular afferents, and standing subjects tend to sway toward the anodal stimulus and/or away from the cathodal stimulus [5]. GVS can induce a virtual sense of acceleration (V-GVS hereafter) without an expensive motion platform (Fig.1)[5]. Properly coordinated with the more common visually produced vection (VPV hereafter), the virtual sense of acceleration can suppress MS and enhance the VR experience [6].

For such interface application, it is requested to be stimulation corresponding to multi-dimensional movements. In previous works, the effects of GVS was almost laterally one dimensional, and the kind of GVS was defined by the polarity and place of electrodes. Because the effect of GVS is monotonic to the amount of current, the current through vestibular must be the principal factor. When the current pathways were multiple, the multi-dimensional effect might be possible.

2. Purpose

In this study, we propose a model of three current pathways for GVS. To confirm the presence of the pathways, DC resistances through head were measured in Experiment 1. In Experiment 2, the sway of standing subject was measured as the multi-dimensional effect of GVS through the three pathways.

This study describes the modeling the current path in galvanic vestibular stimulations for virtual sense of

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acceleration. The research that presumes the brain wave caused by the action potential of the brain cortex is the same kind of analysis[7]. On the other hand, this analysis has aimed at the analysis concerning the distribution of the penetration electric current in the low frequency band, because it has aimed at the analysis under the GVS situation. How the amount of the current that passes the vestibular changes by arranging the electrodes is considered in this study.

3. Model of Current Pathway

First of all, we proposed a current path model of human head for GVS. GVS uses direct current or low frequency current < ~3Hz. In such frequency, bones of cranium works as insulator. The current path through head in GVS should be soft tissue around foramina through bones. Vestibular is placed in the bone of cranium. It has three foramina through the bone, auditory canal, internal acoustic meatus, eustachian tube. These foramina should work as the effective current paths for vestibular . The model of current paths of GVS is shown in Fig..2. It has three current paths which work as three shortcut resistances in an electrical closed circuit of the head..

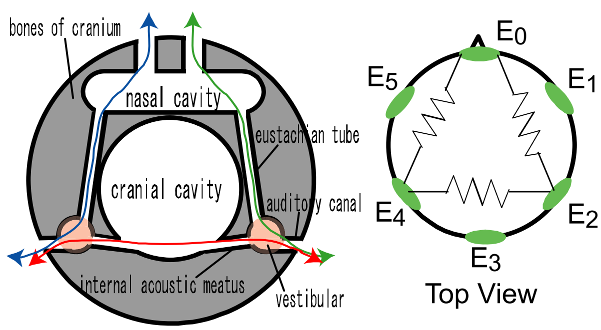


Fig. 2 Model of current pathway through the vestibular: Anatomical hypothesis (Left), Electrical hypothesis (Right)

When the paths through the head worked as shortcut pathway, the DC resistance between the electrodes around foramina through bones should be smaller than the resistance between the electrodes placed away from the foramina. We measured the resistance between the electrodes arranged around a head to verify the hypothesis.

4. Experiment 1: Measurement of Resistances through Head

4.1. Measurement Apparatus

Fig. 3 shows the arrangement of electrodes. Each electrode placed as follows.

E_0: Center of the forehead
E_1: The right temple
E_2: Behind of the right ear
E_3: Center of the nucha
E_4: Behind of the left ear
E_5: The left temple

Those electrodes were arranged in the plane that inclined from a horizontal plane by 34 degrees. Those were arranged separating at most equal intervals.

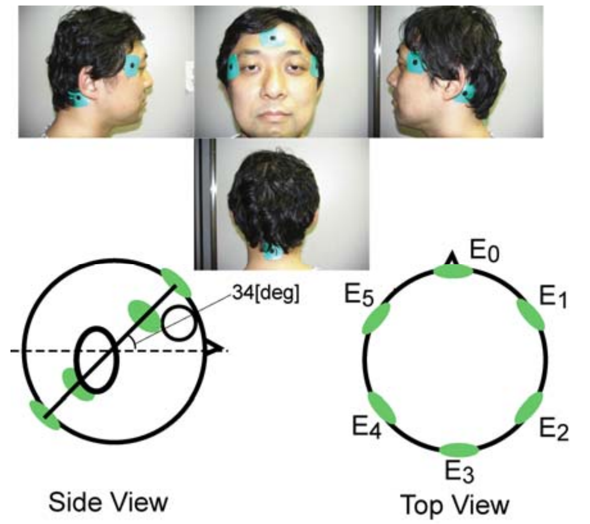


Fig. 3 The arrangement of electrodes on the head

4.2. Results of Experiment 1

Table 1. Resistance and Distance among electrodes

Rij[kΩ]: Resistance between Ei and Ej	Dij[cm]: Distance between Ei and Ej	N: N times of π/6 as the central angle
R_{01}= 1.2	D_{01}= 9.1	1
R_{12}= 1.2	D_{12}= 12.8	1
R_{23}= 1.0	D_{23}= 10.0	1
R_{34}= 1.3	D_{34}= 10.2	1
R_{45}= 1.1	D_{45}= 10.5	1
R_{50}= 1.2	D_{50}= 10.1	1
R_{02}=0.8	D_{02}= 21.9	2
R_{24}=0.8	D_{24}= 20.2	2
R_{40}=0.8	D_{40}= 20.6	2
R_{13}=1.5	D_{34}= 22.8	2
R_{35}=1.4	D_{34}= 20.7	2
R_{51}=1.6	D_{34}= 19.2	2
R_{03}=1.2	D_{03}= 31.9	3
R_{25}=1.4	D_{03}= 31.9	3
R_{03}=1.4	D_{03}= 30.8	3

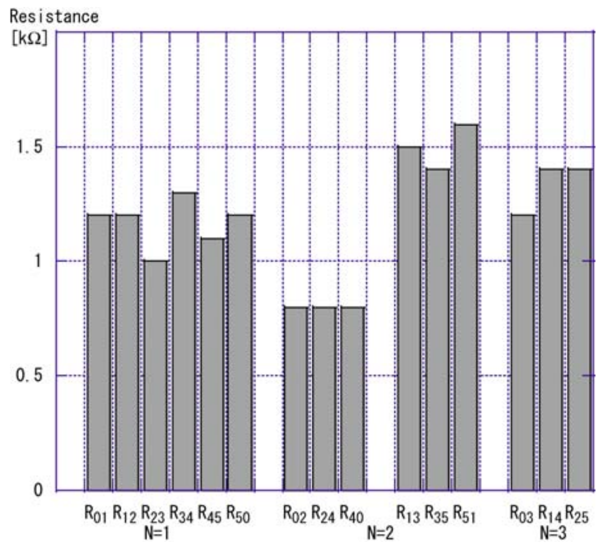


Fig.4 The resistances between electrodes

The measured resistances and distances among electrodes are shown in Table 1. Fig.4 is a graph of the resistances rearranged in order of the distance. R02,R24 and R40 were especially smaller than the other resistances of same category of distance. This result supports the presence of shortcut pathway between each two electrode among E0,E2 and E4. This affirms the electrical hypothesis of Fig.2.

5. Four electrodes arrangement to realize multi-dimensional stimulation through the current paths

We propose four electrodes arrangement in Fig.5 as a method to realize multi-dimensional stimulation through the three current paths. Four independently controllable electric potentials are necessary to control three independent currents in a closed circuit. The added resistance R_{AD} between electrode A and D is an ineffective current pathway for vestibular, because the major current pathway should be the nasal cavity and the eye balls as the soft tissue. If R_{AD} was too small, the three effective currents could not be controlled independently. In Experiment 2, the controllability was evaluated by the sway of standing subject under the multi-dimensional GVS.

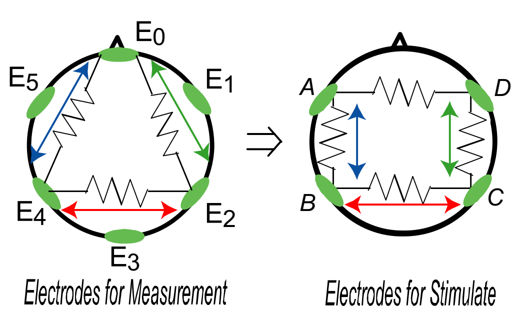


Fig.5 Electrodes arrangement for multi-dimensional GVS

6. Experiment 2: Measurement of the sway of standing subject under GVS through the three current pathways

6.1. Experimental Apparatus

Fig. 5 shows the arrangement of electrodes and stimulators. Each stimulator had a 12V battery as an independent power supply. Each stimulator had no electric connection except for electrodes.

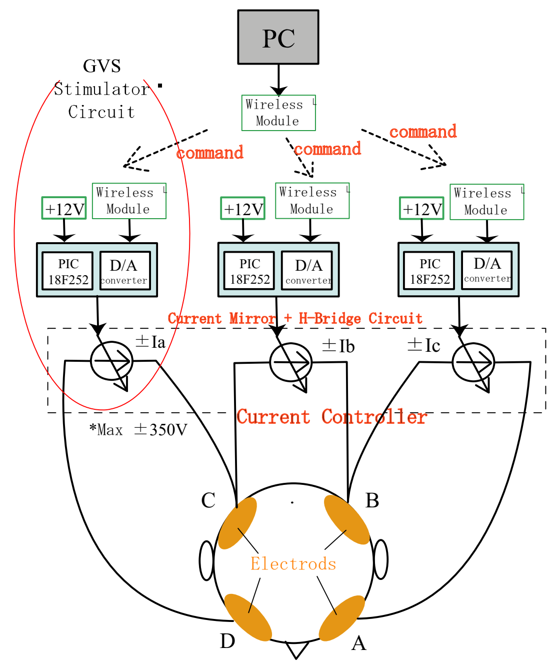


Fig.5 Multi-dimensional GVS stimulator system

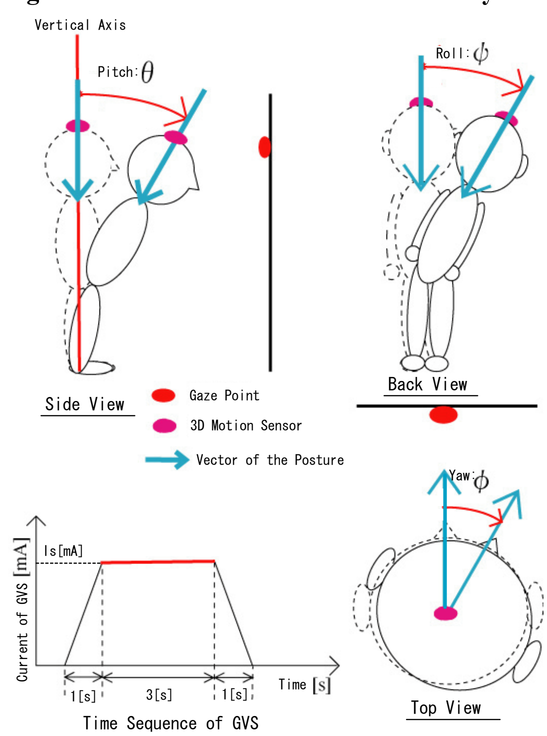
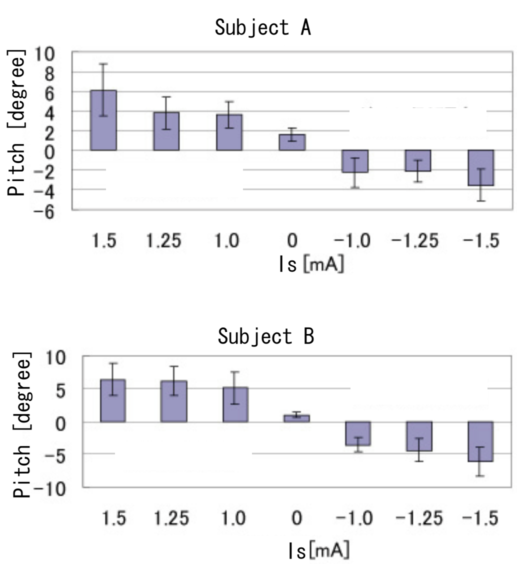


Fig.6 Measurement method of the sway under GVS

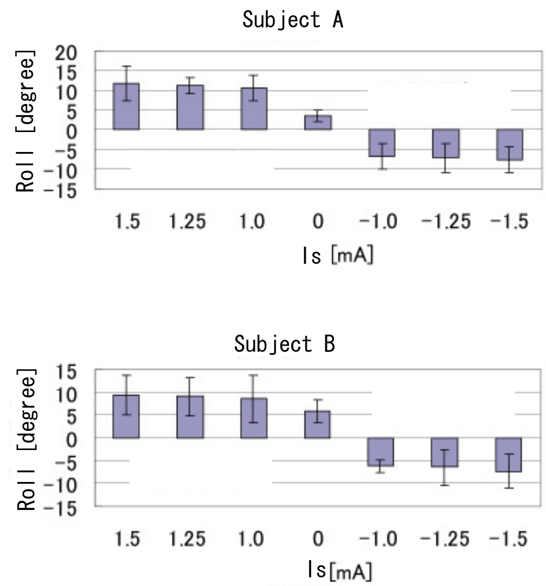
Fig. 6 shows the measurement method of the sway of standing subject under the effect of GVS. Each stimulate had a stable current period of 3[s] and increase and decrease periods of 1[s]. The stable current I_s was chosen from the range -2.0~+2.0[mA]. Three current pattern conditions were selected as shown in Fig.7(d) to evaluate the effect for each postural angle. Subjects were three adult males. Instructions for the subjects were as follows: Stand with both ankle bones touching each other with your hands crossed and touching the opposite shoulders. Stand without shoes on, if possible, and look straight ahead at a target about 3 feet in front of you. Try to stay in this position for 30 sec before start of experiment. (The standing condition is known as Romberg's test.)

6.2. Results of Experiment 2

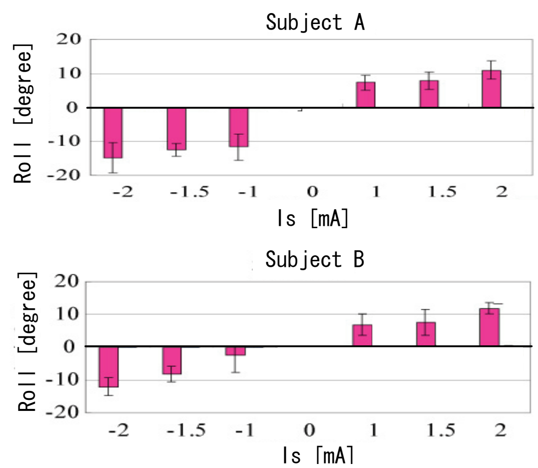
The measured sway angles under each current pattern condition are shown in Fig.7. In pitch and roll conditions, the sway direction was equal to anodal side. These results agree previous findings.
In yaw condition, .the yaw rotating sway was observed. It is a new finding in GVS. The rotational direction of this sway was also synthesis of each direction to anodal side in both of lateral currents, I_{AB} and I_{DC}.
The yaw rotating sway responded to the polarity of current in the yaw condition of current pattern. It means that the resistance R_{AD} of the ineffective path should be sufficiently large from the viewpoint of controllability. As the result, this four electrodes arrangement is effective to realize multi-dimensional GVS.



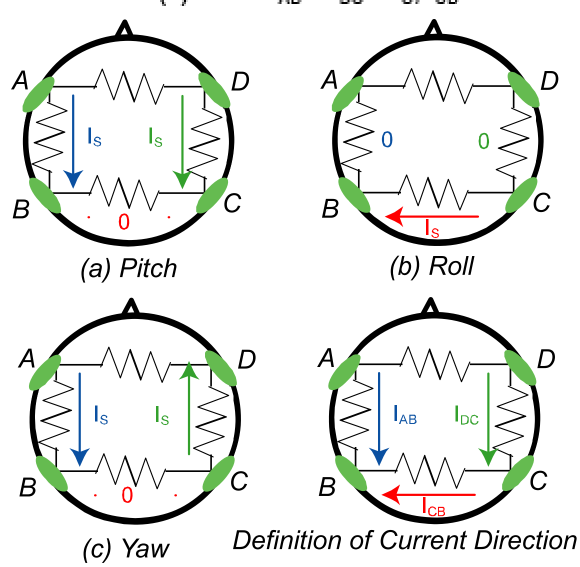
(a) Pitch: $I_{AB} = I_{DC} = I_s$, $I_{CB} = 0$



(b) Roll: $I_{AB} = I_{DC} = 0$, $I_{CB} = I_s$



(c) Yaw: $I_{AB} = -I_{DC} = I_s$, $I_{CB} = 0$



(d) Current Pattern for each angle

Fig.7 Sway under multi-dimensional GVS

6. Considerations

Multi-dimensional effects were caused by the novel method of GVS through multiple current pathways. It means this new method has sufficient controllability to realize the postural balance controller with three degree of freedom. Of course, there are some points that should be improved. One of them is the place of electrodes in nasal cavity side. Electrodes at temple are placed far from the side of foramina. These should be placed at near the nares from anatomical viewpoint.

A new effect of yaw rotational sway was found. In previous observations, lateral response is the only clear effect of GVS. Multi-dimensional effect by GVS had been doubted. This observation is important not only to realize multi-dimensional equilibrioceptional display by GVS, but also to discuss the mechanism of the phenomena by GVS as follows.

Otolith Hypothesis vs. Semicircular canal Hypothesis: What is the sense organ influenced by the current of GVS? In previous researches, two hypothesis has been discussed as the cause of GVS. Otolith organs and semicircular canals are sense organs in vestibular. Otolith organs response to linear motions, and semicircular canals response rotational motion. In this study, the yaw rotational sway was observed to the anodal side as well as the linear sways of lateral, back and forward direction. Especially, in the yaw condition, the current pattern is composed two lateral reverse directional currents. This result seems to support the Otolith hypothesis. Semicircular canal hypothesis was supported by the observation of sway in bipolar stimulation between mastoids. The responses were including not only lateral responses but also rotational responses [8]. However, the model of current pathway in this study can explain the observation, shown as Fig.8.

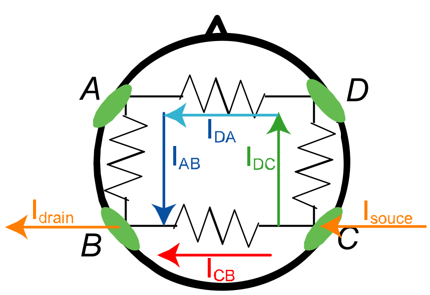


Fig.8 Hypothesis of rotational response caused in bipolar GVS: Bipolar GVS cannot suppress the current path through R_{CD}, R_{DA} and R_{AB}, when the current pathway through R_{CB} is stimulated.

Ratio of contact resistance and internal resistance Each measured resistances in Experiment 1 is sum of contact resistance and internal resistance. In addition, the internal resistance are composed by parallel connection of the resistance of the effective path through vestibular and the resistance of the ineffective path through the skin outside of head bones. On the other hand, the contact resistance depends on the condition between the skin and the electrode. It is a difficult factor for repeatability in GVS. It is necessary to presume the values of these resistances for the accuracy and repeatability in multi-dimension GVS. We have already started the study of the online measurement and presumption method for the resistances [9].

6. Conclusion

This study describes multi-dimensional effects in galvanic vestibular stimulations through multiple current pathways. In this study, we propose a model of three current pathways for GVS. To confirm the presence of the pathways, DC resistances through head were measured in Experiment 1. In Experiment 2, the sway of standing subject was measured as the multi-dimensional effect of GVS through the three pathways. A new yaw rotational sway response was found by the novel method of GVS using four electrodes. The new method is available to realize a multi-dimensional equilibrioceptional display by GVS. This technique is also available for behavioral assist interface. We proposes telecommunication network with Parasitic Humanoid[10,11]. This multi-dimensional GVS can assist the synchronization of head motion to realize synergistic multimodal communication in collaborative multiuser with Parasitic Humanoid.

Acknowledgements
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