Analysis on Effects of Galvanic Vestibular Stimulation on Postural Stability using 3D Motion Analysis

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Abstract: - This paper presents the analysis on effects of GVS(Galvanic Vestibular Stimulation) to mastoid process on postural balance and stability using 3 dimensional motion analysis. The experiments were performed by providing the experimental subjects a bipolar binaural galvanic vestibular stimulation during standing and walking, and then the postural stability was evaluated by 3 dimensional motion analysis system. Postural stability evaluation during standing was performed by a measurement of the deviation of the COP(center of pressure) of experimental subjects who was standing upright on the force plate and was given the currents of 0.5, 1 and 2 mA for 15 seconds. Postural stability evaluation in walking was performed by a measurement of straight walking status after giving the GVS with the currents of 0.5, 1 and 2 mA to the mastoid process located behind the ears. As the results of the experiments of the GVS, it was empirically proven that the changes in the sensory organs including vestibular organ was interpreted by CNS(Central Nervous System) and feedback to body, which makes the posture and the walking stabilized. During standing, the galvanic current provided to the vestibular organ induced the human body to deviate toward the anode, and the magnitude of deviation of the COP presented in the form of sway on the force plate increased as the stimulus intensity increased. During walking, the GVS made the walking path of gait deviated toward anode, which can be a proof of the effectiveness the GVS on posture stability. The major contribution of our study is to provide a novel method for quantitative diagnosis of vestibular organ by investigating the sway of human body during motion using 3D motion analysis techniques, which is different from the previous approaches that only considered the standing condition. Furthermore, it provides a effective guideline for the GVS.

Key-Words: - Galvanic vestibular stimulation, Postural stability, Center of pressure, Motion analysis

1 Introduction

Dizziness occurs as a result of confusion between the two sides of the statoreflex circuits when the afferent information from the peripheral vestibules. Visual organs, depth sensors in the muscles and joints, and other receptors is seamlessly integrated in the brain center and when the efferent commands from the brain center regulate the change in the muscle tensions related to the eye and extremity movements. The main cause of this phenomenon is believed to be the diseases in the peripheral vestibules. The peripheral vestibules quantitatively sense physical forces such as the head’s movement, linear accelerations, and gravity, convert them into electrical signals, and send them to the central system. Using this information, the CNS senses the head movement speed and its head’s position within space and unites the body’s sensory organs and visual organs to maintain postural balance using the body’s position and movement information.

The studies on postural balance according to vestibule information sensing at the CNS include postural stability experiment analysis using physical or electrical vestibule stimuli. These studies introduced methods that use physical vestibule stimulation such as the caloric test that uses temperature, and the rotation chair test that uses rotation [1-4]. However, these test methods perform the analysis by physically stimulating the peripheral vestibules and do not directly stimulate the vestibule nerves. Thus, they cannot analyze clearly the attitude stabilizing functionality of vestibule nerves. The experiment method that uses electrical vestibule simulation, however, stimulates the vestibule nerves...
directly without going through peripheral vestibule sensing by applying electrical stimulation to the ears’ mastoid bones using sinusoidal and DC (galvanic) currents. Thus, it can be used to analyze the responses to postural stability [5].

In the correlation analysis of the electrical signal stimulation of vestibule organs with postural stability by Coates et al. [6], the upper body’s forward and backward direction motions were analyzed by electrically stimulating a single vestibule organ at a stimulus frequency of 0.25-0.28 Hz and at a stimulus strength of 0.8 mA. The results showed that the human body’s response latency time decreased and the COP sway increased with an increase in the stimulus frequency. Corujon et al. analyzed that, from the vestibule organ’s electric stimulus currency input terminals, the cathode side increases the stimulus strength and the anode side decreases it. This shows that, in a standing position, the body is directed towards the anode so that the small single stimulus current in the vestibule system induces the body’s movement towards the anode. In addition, according to the study of Coates [7] on postural stability during walking, in which vestibule organs were stimulated using electrical signals, DC current stimulation in standing position caused body sway; and when one side of the DC stimulus was applied to the anode and the other side, to the cathode, body sway occurred on the anode side.

In this study, we analyzed the effect of the application of vestibular electrical signals on the mastoid bone at static and dynamic conditions. That is, analysis was performed in static and dynamic conditions by applying galvanic current electrical signals with a wide range of stimulus strengths (0.5, 1, and 2 mA) on the mastoid bone, to directly stimulate the vestibule nerve without passing through the peripheral vestibule sensor. In addition, rather than just analyzing the sway in the pressure center movement according to electrical stimuli, as in previous studies, the body movement due to electrical stimuli was analyzed up to the body center movement using a three-dimensional (3D) movement analyzer to more precisely verify the effect of sinusoidal electrical stimuli on postural stability. In addition, to analyze the postural stability during standing and walking when a DC current is applied at a dynamic state per stimulus strength (0.5, 1, and 2 mA), the validity of the vestibule electric stimulus was proven by analyzing the body center movement during standing and the walking path during walking, to analyze the postural stability during standing and walking. This procedure enabled analysis of the postural stability response to vestibule electrical stimuli and the determination of the optimal vestibule nerve stimulation method.

2 Research Methods
2.1 System configuration
In this research, the validity of vestibule nerve stimulation was analyzed by applying a DC current on the mastoid bone, to analyze the effect of vestibule electrical stimuli on the human body’s postural stability under static and dynamic conditions. To measure and analyze the change in the COP due to a weight shift of the subject, force plates with 4 load cells and 3D motion analysis system (Optotrak Certus, Northern Digital Inc., Canada) were used, as shown in Fig. 1.

Fig. 1 The system for postural response measurement during vestibule electric stimulation

2.1.1 Vestibule electrical stimulus system
The electrical stimuli on the vestibule organ were applied using the electrical stimulator system from Jeil Goodhear, Korea, as shown in Fig. 2. To apply the electrical signals on the vestibule organs, electrodes (2x2 cm) were attached to the mastoid bones of each subject. The system’s specifications are shown in Fig. 2.

<table>
<thead>
<tr>
<th>Wave type</th>
<th>DC(Direct current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>1/64, 1/32, 1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, 32, 64</td>
</tr>
<tr>
<td>Current range</td>
<td>0.1 ~ 5mA</td>
</tr>
<tr>
<td></td>
<td>0.1 ~ 0.5 mA(0.05mA increment)</td>
</tr>
<tr>
<td></td>
<td>0.5 ~ 5mA(0.1mA increment)</td>
</tr>
<tr>
<td></td>
<td>1 ~ 5mA(0.5mA increment)</td>
</tr>
</tbody>
</table>

Fig. 2 Vestibule electrical stimulus system
2.1.2 Body sway measurement device
To measure and analyze the change in the COP according to the weight shift, a force platform with four pressure sensors (load cells) was used. The force platform was 600 mm wide, 540 mm tall, and 50 mm thick. The distance between the pressure sensors was 180 mm in the horizontal direction and 280 mm in the vertical direction. When force was applied on the force platform, the signal input from the force platform was converted and outputted as an electrical signal using an amplifier and an A/D converter. By displaying the total change in the pressure center coordinate during a specific time on an orthogonal coordinate system, the average of the displayed part was calculated and the subject’s COP was derived from the average value.

2.1.3 Three-dimensional motion analysis system
The 3D motion analysis system consisted of an infrared camera for observing the infrared LED (IRED) markers that were attached to the body, many auxiliary devices for data acquisition, and a computer for data analysis. To analyze the COP of each human body segment, an infrared camera was installed 1.5 m from the subject; 21 markers were attached to both ear lobes, shoulders, elbows, and wrists, and to the iliac crest, anterior superior iliac spine, greater trochanter, knee joint, malleolus, and xiphoid process [8], as shown in Fig. 3. The three dimensions in the test space were defined as follows: the subject’s front and back were the y axis; his right and left sides, the x axis; and the vertical direction, the z axis. Existing motion analysis cameras with different formats are only capable of two-axis analysis, but the IR motion analysis camera that was used in this study had three position sensors, as shown in Fig. 1, that formed three axes, so that 3D motion measurement was possible using only one camera. The test setup consisted of one IR camera for observing the infrared light diode (IRED) markers, many auxiliary devices for data acquisition, and data analysis computers.

Fig. 3 Markers position of human body

2.2 Subjects
The tests were performed on 10 young adults (seven men and three women; average age: 24.3±1.6 years; body weight: 68.5±2.8 kg; and height: 168.2±1.3 cm). They had no neurological diseases or disorders of the vestibule organs, and had normal muscle-skeletal functionalities. In addition, none of them had participated in similar experiments. The experiment procedure was explained to each of them, but not the purpose of the experiment.

2.3 Test procedures and conditions
2.3.1 Vestibule Electrical Stimulus System (static)
The postural stability response was analyzed in static conditions by applying DC current stimulus waveforms. The subjects were instructed to close their eyes and open their feet 15 cm wide on the force platform. Then their vestibule nerves were directly stimulated at the mastoid bone for 15 seconds by applying DC current with different stimulus strengths. The movement of the body center was observed when 0.5, 1, and 2mA stimulus strength were applied to the anodes (+) of the left and right mastoid bones.

2.3.2 Vestibule Electrical Stimulus System (dynamic)
As shown in Fig. 4, while the subject was walking eight steps on a 3x5m sheet of paper towards the previously shown target point with his eyes closed, different polarities were applied to both their mastoid bones. As in the standing tests, the subjects were repeated three times, including in the controlled experiment; and a total of 19 experiments were performed per subject. To measure the walking path, colored paint was applied on the subjects’ shoes before they walked so that the footprints were printed on the paper when the subjects were walking. It was found that the electrical stimuli that were applied to the mastoid bones caused slight pain. Thus, in this experiment, it was performed after a sufficient amount of anesthesia ointment was applied to the mastoid bones.

Fig. 4 Walking path
2.4 Data collection and analysis method

2.4.1 Body center movement distance and area

To identify the changes in the subjects’ body sway rates according to the vestibule electrical stimuli, the COP area and sway path according to the frequency, strength, and type of stimulus were analyzed. That is, when the COP sway area value was large, the attitude was unstable; but if this value was small, the attitude was stable. The COP area and sway path refers to the total length accumulated while the subject’s COP changed when vestibule electrical signals were applied with the subject standing on the force platform. An IR camera was installed in front of the subject to analyze the center of gravity (COG) and joint angles of each of his body segments. As for the postural stability response data, the state before the application of the vestibule nerve electrical signals was measured. Based on the measured state, the body movement distance and area were analyzed. The accumulated area of the COP was calculated using Equations (1), (2), (3), (4), (5) and (6).

\[ a_i = \sqrt{(x_i)^2 + (y_i)^2} \]  
\[ b_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \]  
\[ c_i = \sqrt{(x_{i+1})^2 + (y_{i+1})^2} \]  
\[ s_i = \frac{a_i + b_i + c_i}{2} \]  
\[ \text{COP area} = \sum_{i=1}^{n-1} s_i(s_i - a_i)(s_i - b_i)(s_i - c_i) \]  
\[ \text{COP sway path} = \sum_{i=1}^{n-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \]

2.4.2 Data analysis method

In this research, to analyze the effect of vestibule electrical stimuli on the human body’s postural stability response, a DC current was applied to the mastoid bone to verify the validity of the vestibule nerve stimulation. One-way ANOVA was performed on the experiment data according to the conditions of the application of the electrical signals, using SPSS 12.0. The p-value for the significance test was below 0.05.

3 Postural Stability Response Analysis and Discussion

3.1 Effect of DC current stimuli: static condition

Tests were performed to study the effect of DC current stimuli on the human body. The effect of a DC current stimulus that was applied at the vestibular system on the postural stability during standing was analyzed. Fig. 5 shows the COP shift data of the subjects according to the DC stimulus current strength and polarity. The movement of the body center increased with the increase in the stimulus frequency. In addition, the center deflected towards the direction where the anode was applied to the mastoid bone.

Fig. 5 COP shift for different currents

Fig. 6 shows the sway area and path of the subjects’ body center sways according to the current strength and polarity of the DC stimulus. The figure shows that as the stimulus current strength increased, the sway path of the body center sway did not significantly change, but the sway area increased.

Fig. 6 COP sway path and area for each amplitude

3.2 Effect of DC current stimuli: dynamic conditions

The effect of the DC current stimulus that was applied to the vestibular system on the postural stability during walking was analyzed. Fig. 7 shows the walking deflection angle data during walking according to the DC current strength and polarity.
When the stimulus current strength increased, the walking path deflected towards the direction where the anode was applied during normal walking. This resulted in the departure of the walking path towards the anode direction. Fig. 8 shows the walking path according to the DC stimulus strength and polarity. It shows that the walking path moves towards the anode that was applied on the mastoid bone. The departure of the walking path increases with the increase in the DC current stimulus. Usually, the subject has no difficulty in walking straight without a visual stimulus; but a bipolar DC current stimulus causes departure of the walking path towards the anode side [9].

While the effect of the input method on the vestibular system during walking is not clear, it is certain that the vestibular system affects the postural stability during walking. The direction of departure of a subject during straight-line walking is consistent with the body center movement that was observed during the standing experiment. In this study, the subject’s body center was made to deflect towards the anode using the DC current stimuli of 0.5, 1, and 2 mA. As in the findings of Richard [9], there was no departure in the direction up to the second footstep, after which a conspicuous directional departure occurred at the third footstep. After that directional departure occurred, the subject recognized the directional departure during walking and walked in a direction that would enable him to return to the original straight line.

Gorden et al. [10] found that if there is no visual stimulus, the proprioreceptor inputs from the lower body, and the vestibular input from the three semicircular canals contributes to the sensing of the walking path. DC current stimuli cause confusion in recognizing planned walking trajectories. That is, if the anode DC current is applied to the right side, it is recognized that the starting point of walking is skewed to the left. Thus, the vestibular stimulus that is applied while standing recognizes that the starting point’s direction is deflected and guides the body to the opposite direction, so that if the anode DC current stimulus is applied to the right side, the body deflects to the right to be able to walk in a straight line. Thus, the departure from the walking path due to the DC current stimulus is related to the sensing of the starting point in a deflected manner.

Fitzpatrick et al. [11, 12] reported that stereo DC current stimuli cause body sways to the anode, or deflect the sensing of the gravity’s direction towards the anode. Such sensing of the sensory system results in the body’s falling towards the anode and its deflection to the anode during the walking period, so that walking is deflected towards the unstably forwarded foot from the right/left side, towards which the foot was forwarded in a stable manner. Thus, the body moves to the left/right during walking. This can be explained as a mechanism that contributed to the direction deflection that was observed in the vestibule stimulation experiment.

4 Conclusion
In the experiments where DC current waveforms was applied, it was observed that the body tilted towards one direction. In addition, depending on whether the current was applied on the positive polarity or the negative polarity, the body tilted towards the opposite side.
In the tests with varying current strength, it was found that the current strength contributed in determining the amplitude of body sway. The body’s motion changes were observed while changing current strength to 0.5mA, 1mA and 2mA in static and dynamic tests; in the static tests, the change in current strength influenced the extent of body’s tilt to each side. And in dynamic tests, the change in current strength influenced the extent of motion walking path’s deflection. Data analysis revealed that the amplitude of body sway and deflection of motion walking path increases with current strength; therefore, we found that the amplitude of body sway and deflection of motion walking path is proportional to current strength.

In the tests with varying frequencies, it was also found that the frequency influenced the results with relation to the period of the sway. The change in the sway was confirmed in the static tests. Currents at 0.5, 1, and 2 Hz were used for the tests, and it was experimentally confirmed that the motion became small and dull with a higher frequency. Thus, from this, we concluded that the motion period is reduced with an increase in the frequency, so that the frequency is inversely proportional to the motion period.

The orientation of the movement according to the current’s polarity was observed at both the static- and dynamic-condition experiments. In the case of the DC current, the direction of the body tilt occurred to opposite directions according to whether the polarity was positive or negative. Thus, by implementing such a vestibular organ stimulation system for patients with disorders in maintaining body stability, it will be possible to overcome disabilities in a medical manner by tilting the body in a way that fits the conditions.

Up to now, few researches have quantified the functionality of the vestibular system, because it is not easy to evaluate the conditions of the vestibule system in a comprehensive manner. It is thus concluded that the vestibular electrical stimulus that is proposed in this thesis effectively affect the postural stability in static and dynamic conditions. In the future, attitude stabilization tests under static and dynamic conditions will be performed on patients with vestibular system disorders or on old people; and based on their results, utilization in the rehabilitation of patients with stability disorders, dizziness, etc. is expected.

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