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Non-Linear Analysis of Stabilograms with Alcoholic Intake

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Abstract— **Equilibrium function in the cerebellum (vestibulo-cerebellar system) can deteriorate under the influence of alcohol. In the Romberg posture, the center of gravity, which was measured every 50 ms by stabilometry, appeared to shift with alcohol ingestion. In the previous study, a locus in the center of gravity (stabilogram) was converted to values of statistical indices such as area of sway, total locus length, and locus length per unit area, although these indices could not always distinguish between the statokinesigrams sampled from seven healthy young males in sober and intoxicated states. This measurement was made with an AMTI force plate. In this study, "translation error" was estimated in a *d*-dimensional embedding space in order to compare statokinesigrams recorded before and after the ingestion of doubly diluted brandy in 30 s ($1 \leq d \leq 10$). We succeeded in validating a stochastic differential equation as a mathematical model of the body sway. The randomness in the model was preserved after alcohol intake and significantly increased in the medial/lateral direction. Visual information referred by the postural control system when standing might be interfered by the effects of intoxication, which was regarded as disturbance. This method is considered to be useful to diagnose the disorders of the vestibulocerebellar system.**

I. Introduction

Stabilometry is considered useful as a body equilibrium test for investigating overall impairment of the balance function [1]. To increase the diagnostic value of stabilometry, a method using stabilometry and analytical indices of the recorded body sway (stabilogram) has been proposed [2]. The locus length per unit area represents minute alterations of postural control and evaluates the function of spinal proprioceptive postural control.

Healthy subjects and patients with disequilibrium are compared to evaluate the usefulness of an analytical approach to stabilometry, but experiments involving these subjects are difficult to perform due to the difficulty of recruiting subjects and the consequent problems with reproducing data due to the small number of subjects. One method to overcome these problems is artificial reproduction of disequilibrium by alcohol ingestion. The function of the cerebellum (specifically, the vestibulocerebellar system) controlling the vestibulospinal reflex is pharmacologically inhibited by alcohol ingestion, and the pattern of the stabilogram alters after alcohol ingestion [3]. Many investigators have reported the effects of alcohol on the oculomotor system [4]-[8] and on the vestibular system through positional nystagmus [9][10]. Since the cerebellar function controlling the vestibulospinal reflex (the vestibulocerebellar system) is pharmacologically inhibited by alcohol ingestion, postural instability after alcohol ingestion is observed after alcohol ingestion. The change in the sway of the center of gravity is induced by the alcohol ingestion; this connection has been quantitatively evaluated by the correlation between the blood alcohol concentration (BAC) and the body sway [8][11]. However, it has been difficult to classify the sway path based on the values of the indices, such as outer and effective areas, total locus length, and locus length per unit area [12]. On the other hand, it has been clarified that the density of measurement points in a stabilogram is related to the stability of the standing posture, based on which functional inhibition by alcohol ingestion became detectable based on the index in the stabilogram, called sparse density [13]; this suggests that, mathematically, deterioration of equilibrium can be detected by analysis of a dynamic model incorporating structural stability, while not using any index focusing on the geometrical characteristics of the overall stabilogram.

Stabilograms were described by a stochastic process [14]-[16]. The anterior-posterior direction y was considered to be independent of the lateral direction x [17]. According to the stochastic analysis of the authors, the differential body sway is well described by a Gaussian process added to the gradient of the potential function whose minimal points exist on their center of each plantae [18]. Non-linear analyses, such as the surrogate analysis or the correlation dimension estimation from the Grassberger–Procaccia algorithm, is known to be methods to evaluate whether the time series are generated by a Gaussian process or the other stochastic process [19]. However, it is difficult to specify the generator of a time series when the data is contaminated by observation noise. A stabilometer does not have enough resolution to compare the differences in the center of gravity for each time step. The Wayland algorithm [20] has been developed to conquer sampling errors in the statistical signal processing of the contaminated time series.

In this study, to measure the degree of determinism of a mathematical model reconstructing the stabilogram, we estimated a statistical index, translation error, by employing a time-series analytical method, the Wayland algorithm

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(Appendix), and compared changes in the index after alcohol ingestion.

II. Material and Method

A gait analysis system (Force Plate, AMTI Ltd.) was used as a stabilometer. The coordinates of the output of this system, which were the measurement points, were determined in units of centimeters and a reading error of 2 mm. The duration of measurement and sampling frequency were set at 120 seconds and 20 Hz, respectively, and noise was removed using a 10-Hz low-pass filter.

The subjects were seven male university and graduate school students aged 20–26 years with no past medical history of diseases of the ear or nervous system, who were being examined in a routine medical check-up at the Health Administration Office of Nagoya University.

The test was performed following the criteria established by the Japan Society for Equilibrium Research [21]. The subject stood straight with the feet together so as to align the center of the soles at the reference point of the stabilometer. In the test with the subject's eyes open, a target with a diameter of about 2 cm, was placed 2 m in front of the subject at eye level, and the subject stared at the point. Stabilometry was recorded at the following times:

(1) Before alcohol ingestion

(2) During a 110-minute period from 150 seconds to 113 minutes after alcohol ingestion

The subject stood straight for one minute to stabilize the standing posture (Romberg posture); immediately thereafter, the subject's body sway was measured continuously for one minute with eyes open and again for one minute with eyes closed. After the measurement, the subject sat for two minutes. In (2), the measurement was consecutively repeated 22 times, resulting in measurements with open and closed eyes at 5-minute intervals. These 22 measurement times were designated as stages 1 to 22 in that order.

The volume of alcohol ingestion was set so as to adjust the blood level to 0.6 mg/m*l* based on an equation for the blood alcohol level (given below), and the subject drank 2-fold diluted brandy within 30 seconds. This blood alcohol level is classified as the Euphoria (slight intoxication), and the following clinical findings appeared: rapid pulse and breathing, slurred speech, and loss of behavioral inhibition [11]. The blood alcohol level, C_p, is determined by the following equation, in which 0.789 [g/ml] is the specific gravity of alcohol, and the numerator and denominator represent the amount [g] and volume of distribution of the ingested alcohol, respectively:

$$\begin{aligned} C_p[mg/ml] &= (alcohol\ concentration)[\%] \\ &\times (amount\ of\ alcohol\ consumed)[ml] \\ &\times 0.789[q/ml]/0.53[l/kg]/(Weight\ of\ subject)[kg] \end{aligned}$$

The details of the study were fully explained to the subjects beforehand, and consent was obtained. No drug or invasive treatment other than alcohol was used.

The *x*-*y* coordinates were measured at each sampling with open and closed eyes and recorded as a text file. The file was then processed using our Visual Basic program to calculate the indices. The obtained data of the tests with open and closed eyes were converted to time-series of the center of gravity in the lateral and anterior-posterior directions (where the rightward and forward are positive in the *x* and *y* directions, respectively).

To investigate changes in the total locus length and the translation error [20] calculated before and after alcohol ingestion, the values at each of the 22 measurement stages after alcohol ingestion and that before the alcohol ingestion were compared by the Wilcoxon signed-rank test, setting the significance level to be 0.05. Generally, a one-sided test is used because the feature value increases after alcohol ingestion. However, we employed a two-sided test because the tendency of the translation error was unclear.

III. Non-Linear Analysis

In each of the seven subjects, stabilometry was performed before (stage 0) and 22 times after alcohol ingestion (stage 1-22), respectively, and stabilograms were recorded. The following items were investigated in all records:

The stabilograms of all subjects were divided into those with open and closed eyes, and the Wayland algorithm was applied to compare the record of the seven subjects immediately before alcohol ingestion with that at each stage after alcohol ingestion.

To investigate differences in the translation errors calculated above between the value before alcohol ingestion and that at each stage in the equilibrium recovery process, the Wilcoxon signed-rank test was employed.

IV. Results

According to the measured stabilograms, the body sway spread over a wide area after alcohol intake. The total locus length significantly increased in stages 8 with respect to the measurements taken before the alcohol intake (Fig. 1).

In the lateral direction (*x*) for the eyes open condition, the maximum value, about 1.1, was noted at an embedding dimension of d=1 before alcohol ingestion, whereas the value temporarily stabilized at d=2 around stage 10; the value then generally decreased with time, and the overall value rose near stage 20.

In the anteroposterior direction (*y*) with eyes open, the maximum value (about 1.0) was noted at d=2 through d=4 before alcohol ingestion, and the value generally decreased from stage 10 to 15. By stage 20, the value mostly recovered to that before alcohol ingestion.

In the lateral direction (*x*) with eyes closed, the maximum value, 1.1, was noted at d=2 before alcohol ingestion and then gradually decreased thereafter. In stage 15, the value slightly rose and reached a maximum value of about 1.4 at d=1, and then decreased again in stage 20.

In the anteroposterior (*y*) direction, the maximum value, about 1.2, was noted at d=1 before alcohol ingestion and then decreased from stage 5 to stage 10. The value returned to the

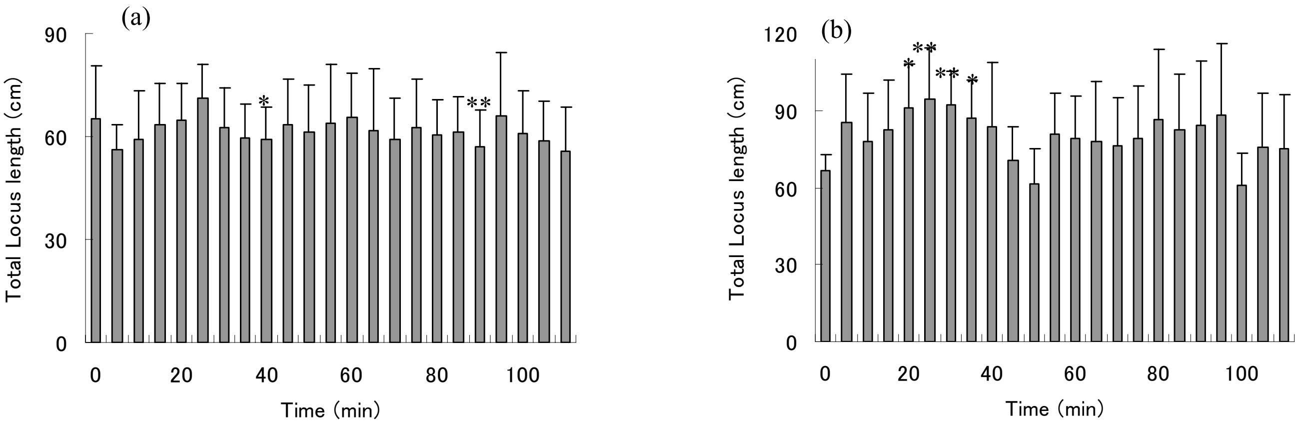

Figure 1. Time-course changes in total locus length. Eyes open (a) and closed (b).

original level by stage 15.

The translation error mostly increased in the lateral direction with eyes open. Regarding the stage in which a marked increase was observed, none of the observed distributions suggested the possibility that the control system of the standing posture is by a *d*-dimensional deterministic model. In the other time series, the translation error generally decreased. A decreasing tendency was frequently observed before stage 17, whereas this tendency mostly disappeared after stage 18.

V. Discussion

In this study, the degree of freedom of the dynamical system to maintain the Romberg posture in humans was estimated based on nonlinear analysis. Of the previously used analytical indices of stabilograms, alcohol ingestion has been detected by employing the sparse density [13]. Since the sparse density depends on the micro-structure of the temporally averaged potential controlling the stochastic differential equation (SDE), alcohol ingestion may change this; a mathematical investigation was performed to test this hypothesis, assuming that the mathematical model describing the body sway is an SDE as

$$\frac{\partial x}{\partial t} = -\frac{\partial}{\partial x} U_x(x) + w_x(t), \qquad (1.1)$$

$$\frac{\partial y}{\partial t} = -\frac{\partial}{\partial y} U_y(y) + w_y(t), \qquad (1.2)$$

where $w_x(t)$, $w_y(t)$ are white noise terms and U_x, U_y express their temporally averaged potential functions. Our hypothesis was validated, and the mathematical meaning of the stabilogram could not be observed from any other analysis of previous indices.

Employing the method introduced in this paper makes the following interpretation possible.

Excluding the time-series data of the lateral direction with eyes open, the estimated translation error decreased after alcohol ingestion, suggesting that the degree of freedom of the system decreased. In mathematical logic, this phenomenon occurs when the noise amplitude decreases.

Variation in the lateral direction with eyes open showed opposite changes to this and contained many irregular components. Normally, visual information is referred by the postural control systems while standing, but alcohol ingestion may have served as an external disturbance. This tendency continued for about 2 hours. This method is very likely to be useful to diagnose diseases of the vestibulocerebellar system (such as central paroxysmal positional vertigo).

In the conventional observation system, identification of the mathematical model is difficult because the noise amplitude changes in each experiment. Thus, the Double-Wayland algorithm has been developed, and we re-applied the Wayland algorithm to temporal differences of the time series and developed (Appendix). However, the tendency of the appearance of the translation error in the embedding dimensions was stable in the body sway investigated in this study, and, thus, only the Wayland algorithm was applied.

Excluding the lateral direction with eyes open, variation of the translation error became undetectable mostly after stage 18 (after about 90 minutes), suggesting that the subjects recovered from alcohol-ingestion-induced disequilibrium at roughly this point in time.

VI. Conclusion

In this paper, we have suggested the possibility of detecting alcohol-ingestion-induced reduction of the equilibrium function and its recovery process by applying the Wayland algorithm to the stabilograms in the *x* and *y* directions. We have also suggested that responses to alcohol ingestion are output by the postural control system while shows different patterns in the lateral and anterior-posterior directions. In the next step, parallel measurements as breath alcohol concentration would have been performed on the same subjects in order to connect the alcohol impact to the vestibular system.

VII. Appendix

An attractor is reconstructed from a time series. The attractor is constructed by means of embedding the time series data proposed by [22] in the phase space. Embedding is a method that draws an orbit in phase space supposing a vector whose elements are the values for when the time elapses from t to Δt, 2Δt, …, (N-1) Δt as a point in N dimensional phase space (embedding space). N and Δt are referred to as the embedding dimension and the sampling time, respectively. The delay coordinates $\{\mathbf{x}(t)\}$ can reconstruct a continuous trajectory without crossing into an embedding space that has a high dimension. If we only resample the time series at every delay time τ when the auto-correlation coefficient $\rho(\tau)$ is regarded as zero, components of the delay coordinate cannot linearly correlate with each other. In this study, the auto-correlation function $\rho(t)$ was estimated from the time series data [19] and regarded as zero when $\rho(t)$ decreased below $1/e \cong 0.37$ for the first time $(t \geq 0)$.

The Wayland algorithm assumes that the difference vectors $\mathbf{v}(t) = \mathbf{x}(t+\tau\Delta t) - \mathbf{x}(t)$ in the embedding space characterize the nonlinear variations of the trajectories and estimate the translation error in an m-dimensional embedding space (m = 1, 2, …, 10). Here, $1/\Delta t$ is 20 Hz. A linear correlation between adjacent vectors $\mathbf{x}(t)$ and $\mathbf{x}(t+\tau\Delta t)$ is eliminated by resampling the time series with respect to each embedding delay τ.

(i) A series of delay coordinate vectors $\{\mathbf{x}(t)\}$ is embedded in each space.

(ii) M onset periods t_0 are randomly selected.

(iii) The values of

$$E_{\text{trans}}(t_0) = \frac{1}{K+1}\sum_{i=0}^{K}\frac{|\mathbf{v}(t_i) - \bar{\mathbf{v}}|}{|\bar{\mathbf{v}}|} \quad (2)$$

are standardized by the average of the difference vectors at $K+1$ points $\{\mathbf{x}(t_i)\}_{i=0}^{K}$.

$$\bar{\mathbf{v}} = \frac{1}{K+1}\sum_{i=0}^{K}\mathbf{v}(t_i) \quad (3)$$

is obtained at every onset period, where the K points nearest to $\mathbf{x}(t_0)$ are selected as $\{\mathbf{x}(t_i)\}_{i=0}^{K}$.

(iv) The median of the M values of Eq. (2) is extracted.

(v) Q medians are obtained by repeating the above steps.

The translation error E_{trans} is estimated by the expectation value of these Q medians.

The Double-Wayland algorithm includes the following additional steps.

(vi) Translation errors, E_{trans}', are derived from temporal differences in the time series data (differenced time series) $\{\mathbf{x}(t+\tau) - \mathbf{x}(t)\}$ by the Wayland algorithm outlined above.

(vii) If a differential equation system that included stochastic factors was the generator of the time series, the flow would not be smooth. In such a case, a significantly higher number of translation errors might be estimated in the last step than in step (v).

In this study, we set the conditions of the coefficients M, K, and Q to be 51, 3, and 10, respectively [20].

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