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Rhythm-Fluctuation-based Evaluation Platform for Gait Training of Parkinson's Disease Patients

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***Abstract*—Gait training using rhythmic auditory cue showed training effect on gait dynamics of patients with Parkinson's disease (PD). On the other hand, 2 indicators of gait rhythm fluctuation, coefficient of variation (*CV*) and scaling exponent *α*, can evaluate severity of PD. However the gait training was not evaluated by both of these indicators at a time. In this paper, we aim to propose rhythm-fluctuation-based evaluation platform for gait training of PD patients. This platform consists of *CV* and *α* of stride interval. Specifically, we evaluated 3 types of gait training by calculating the change amount of *CV* and *α*. The training types are 1) interactive Walk-Mate (WM) gait training, 2) fixed-tempo Rhythmic Auditory Stimulation (RAS) gait training, and 3) Silent Control gait training. The training program was continued for 4 days. The first trial in each day was baseline walking trial without rhythmic cue. The second and the third trials were training trial corresponding to the training condition. Twenty-four PD patients walked for about 2 minutes in each trial. These patients divided into 3 groups about training type. As a result, WM gait training improved *α* and *CV* significantly. RAS gait training tended to improve *CV*, but it seemed to worsen *α* of gait rhythm. These effects of RAS gait training were marginally significant. However, Silent Control training did not show the significant effect on both of the indicators. From these results, the rhythm-fluctuation-based evaluation platform was successfully used to evaluate each type of gait training. In addition, the rhythm-fluctuation-based evaluation platform detected the difference between WM gait training and RAS gait training by *α*.**

I. Introduction

A gait rhythm often synchronizes when two people walk over ground side-by-side [1], [2]. The gait rhythm synchronization has been applied to gait rehabilitation of Parkinson's disease (PD), hemiplegia, and so on [3]–[5]. PD is one of the neurodegenerative disorders. In PD patients, impairments of rhythmic movement were often observed, such as gait disturbances [6], [7]. A key point of gait rehabilitation of PD patients is the dynamics of provided rhythmic cue. Mainly two types of gait rehabilitation is proposed. One is rhythmic auditory stimulation (RAS) gait training, which is unidirectional intervention using fixed-tempo rhythmic auditory cue [3]. The other is Walk-Mate (WM) gait training, which is gait training using interactive rhythmic auditory stimulation [4]. There are difference of effect between types of gait training [8]–[11].

On the other hand, gait rhythm fluctuation is related to severity of PD. In previous study, the severity of postural reflex disorders (PRD), which is one of the clinical symptoms in PD, was evaluated by 2 indicators of gait rhythm fluctuation [12]. One is coefficient of variation (*CV*), which can mainly differentiate the presence or absence of PRD. The *CV* represents the amplitude of gait rhythm fluctuation [13]. The other is scaling exponent *α*, and it can mainly differentiate the severity of PRD. The *α* indicates time-series structure of gait rhythm fluctuation, and it is calculated by detrended fluctuation analysis (DFA) [14]. From these results, the combination of *CV* and *α*, have potential to evaluate gait training of PD patients. In this study, we focused on these indicators, *CV* and *α*.

However, the gait training was not evaluated by these indicators at a time. In previous study, the carry-over effect of gait training using rhythmic cue on *α* of gait rhythm was reported by Hove *et al*. [3]. Moreover, the relearning effect of 4-day training on *α* was reported by Uchitomi *et al*. [4]. The relearning effect is linear trend of day-by-day change trend of *α*, or *CV*. Improvement of *CV* has not been reported in [4]. If we evaluate change amount of *CV* between pre-training and post-training, sensitivity of evaluation will be improved.

From these backgrounds, the purpose of this study is to propose rhythm-fluctuation-based evaluation platform for gait training. We reanalyzed the data of Uchitomi *et al*. [4], and evaluated the interactive WM gait training, fixed-tempo RAS gait training and Silent Control training. To improve the evaluation method for gait training, we focused on change amount of *CV* and that of *α* from pre-training to post-training. Specifically, we tested difference of average of *CV* and that of *α* between pre-training and post-training in each training. In addition, we compared the training effect on change amount of *CV* and that of *α* between 3 types of gait training.

In section II, the experimental system, participants, and gait training program were explained. Then, the rhythm-fluctuation-based evaluation platform for gait training were described. In section III, the result of each gait training, and the result of comparison of training effect between different types of training were presented. In section IV, the difference of training effect between 3 types of training was discussed. Section V is conclusion.

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II. Method

A. Experiment system

Fig. 1 shows the experimental system. The training using rhythmic auditory stimulation was provided by overhead-type stereo headphones (HP-RX500, Victor, Japan). The cue rhythm was generated by Walk-Mate model [4], [11], which is implemented on laptop PC (CF-W5AWDBJR, Panasonic, Japan). Walk-Mate model is described by hierarchical phase oscillator [4]. Module-1 is the mutual entrainment with human gait rhythm. It is written by (1), and is called as "Kuramoto model" [15].

$$\dot{\theta}_m = \omega_m + K\sin(\theta_h - \theta_m). \quad (1)$$

Module-2 is the phase control. It is described by (2), and this module contributes to set phase difference between human and sound cue to target value.

$$\dot{\omega}_m = -\mu\sin(\Delta\theta_d - \Delta\theta_{hm}), \quad (2)$$

where natural frequency of phase oscillator ω_m, the phase difference between human and phase oscillator $\Delta\theta_{hm} = \theta_h - \theta_m$, phase of oscillator θ_m and phase of human θ_h are the variables. The 0 [rad] of θ_m and θ_h are defined as stimulus timing and foot contact timing. The initial value of ω_m was set to preferred walking tempo, determined by the first 20 steps of each trial. In WM gait training, to control the phase difference between human and sound cue, the target phase difference $\Delta\theta_d$ was set to 0.2, and coupling constant K was set to 0.5, and μ was set to 0.32. These value were same settings as previous studies [4], [10], [11]. RAS training was realized by unidirectional fixed-tempo auditory cue (K = 0, μ=0). In Silent Control gait training, rhythmic auditory cue were not provided. The gait rhythm was measured using foot switches (OT-21BP-G, Ojiden, Japan) attached to the shoes. This information was transmitted to laptop PC wirelessly every 10ms using transmitter (S-1019M1F, Smart Sensor Technology, Japan) and receiver (WM-1019M1F, Smart Sensor Technology, Japan). The accuracy of phase difference between human footsteps and auditory cues were confirmed in [4], [10], [11], even though the lag between laptop PC and sensor exists.

B. Participants and gait training program

24 PD patients (mean ± SD of age: 71 ± 8 years, Male: Female = 13 : 11) were participated. The median value of modified Hoehn and Yahr scale (HY) was 2.5, and the range of HY was from 1.5 to 3. Participants were divided into 3 groups. Training program was consecutive-four-day walking task (see Fig. 2). All participants walked three times a day, from the first day to the third day. The first trial in each day was baseline walking without any cue. The following two trials were gait training trials corresponding to training groups. All walking trial was for about 2-3 minutes.

Before the participation in this experiment, all participants were informed using written materials, and we obtained prior written consent. The procedure of this study was approved by Kanto Central Hospital Ethics Committee.

C. Rhythm-fluctuation-based evaluation platform

Rhythm-fluctuation-based evaluation platform is constructed by the combination of 2 dynamic indicators. One is coefficient of variation (*CV*). The other is scaling exponent *α*. The first 5 stride data and the last 5 stride time data were not analyzed at least, to eliminate transient walking period.

1) CV: To quantify amplitude of gait rhythm fluctuation, we used *CV* of stride interval. This indicator is calculated by (3).

$$CV = \frac{u_{sd}}{\langle u \rangle} \times 100 \quad [\%], \quad (3)$$

where u_{sd} is standard deviation of stride interval, and $\langle u \rangle$ is average of stride interval. *CV* of PD patients is larger than that of healthy people (usually about 2-3%) [13]. In fact, decrease of *CV* indicates the improvement of gait rhythm generation.

Fig. 1. Device for gait training using rhythmic auditory cue.

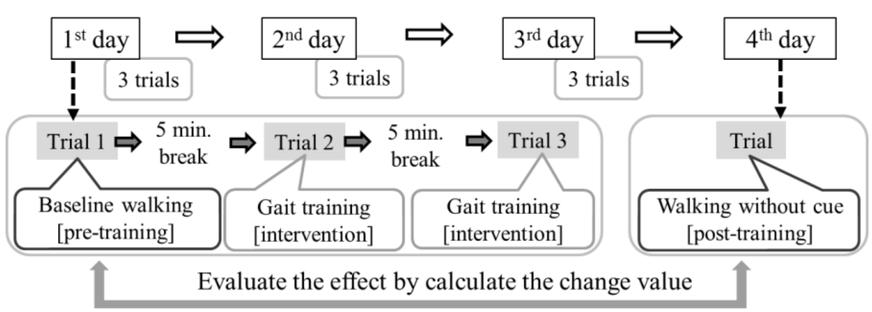

Fig. 2. Training program. Each participants walked the same corridor for about 2-3 minutes total 10 times in four consecutive days. The first walking trial in each day is baseline walking without any rhythmic cue. From 1st day to 3rd day, there were 2 training trials using rhythmic cue after baseline trial. To verify the training effect, we analyzed the baseline data of the 1st day (Pre-training data) and the baseline data of the 4th day (post-training data).

2) Scaling Exponent: To estimate the fluctuation property of stride interval time series, scaling exponent α is calculated using DFA [14]. There were 2 steps in DFA. Step 1 is integration of time series data, described as (4). In step 2, the integrated data were divided into the non-overlap same size box. The scaling structure of detrended fluctuation to divided box size was estimated, described as (5).

$$y(k) = \sum_{k=1}^{i} \left[u(k) - \langle u \rangle \right] \quad (i = 1, \ldots, N). \tag{4}$$

$$F(n) = \sqrt{\frac{1}{N'} \sum_{k=1}^{N'} (y(k) - y_n(k))^2} \propto n^{\alpha} , \tag{5}$$

where $u(k)$ is k-th stride interval and $y(k)$ is the integrated data of the deviation from the average stride interval. The fluctuation $F(n)$ is calculated by the root mean square of the deviation of $y(k)$ from linear trend $y_n(k)$ when the divided box size is n. If α is near 1.0, the time series has $1/f$ fluctuation property. $1/f$ property is often observed in the stride interval of healthy young people [16]. If the α is near 0.5, the time series has white noise property. White noise property is often observed in the stride interval of PD patients [9], [17]. Therefore the increase of α represents the improvement of fluctuation property.

3) Averaged Trajectory on CV-α plane: The individual trajectories in each group from baseline data of 1st day (pre-training) to that of 4th day (post-training) on *CV*-α plane was drawn to quantify the training effect (see Fig. 4(a),5(a),6(a)). Then averaged trajectory between participants in each group was calculated to evaluate the tendency for each group to improve or deteriorate gait dynamics.

D. Statistical analysis

At first, we analyze the training effect in each group. Then we compare the effects of training between interactive WM, fixed-tempo RAS and Silent Control condition.

1) Training Effect in Each Training Conditions: The difference of mean value of *CV* or α between pre-training and post-training were tested to verify the training effect of each training. Three hypothesis shown below were tested by paired- sample t test.

NH-1) *CV* of pre-WM is smaller than *CV* of post-WM, and α of pre-WM is larger than α of post-WM.

NH-2) *CV* of pre-RAS is smaller than *CV* of post-RAS and α of pre-RAS is smaller than α of post-RAS.

NH-3) *CV* of pre-training is the same as *CV* of post-training and α of pre-training is the same as α of post-training in silent control gait training.

2) Comparison of Training Effect between training types: The differences of mean value of the change of *CV* or change of α from pre-training to post-training were tested to compare the training effect between 3 groups. At first, Levene's test was used to test the homogeneity of variance between the 3 groups. If the homogeneity of variance between 3 groups was confirmed, then analysis of variance (ANOVA) was used to test significance of variation among 3 groups. As a post-hoc test, Tukey's honestly significant difference (HSD) test were used, if the significant variance between 3 groups is observed.

3) Threshold of significance level in statistical analysis: Significant level was set to $p < 0.05$, and marginally significant level was set to $p < 0.10$.

III. Result

A. Result about each type of gait training

In Fig. 3, the training effect about interactive WM gait training was shown firstly. The dashed arrows in Fig. 3(a) are individual trajectory on *CV*-α plane. And the solid arrow is the averaged trajectory about interactive WM gait training. The lengths of each trajectories tends to be large, and *CV* decreased, and α increased. The training effect of *CV* and that of α was significant (see Fig. 3(b), and Fig. 3(c)). Specifically, the *CV* in post-WM gait training was significantly lower than that in pre-WM gait training (see Fig. 3(b), $t(7) = 2.8$, $p = 0.01$). This result represents the improvement of gait rhythm generation by WM gait training. Similarly, the α in post-WM gait training was significantly higher than that in pre-WM gait training (see Fig. 3(c), $t(7) = -2.4$, $p = 0.02$). This result indicates the improvement of fluctuation property.

Secondly, the training effect about fixed-tempo RAS gait training was shown in Fig. 4. When we consider the direction of individual trajectory, *CV* tends to decrease, and direction to decrease of α (see Fig. 4(a)). In fact, the difference of *CV* between pre-RAS gait training and post-RAS gait training was marginally significant (see Fig. 4(b), $t(7) = 1.6$, $p = 0.08$). This result tends to suggest that RAS gait training would improve the amount of gait rhythm fluctuation. Moreover, the difference of α between pre-RAS gait training and post-RAS gait training was marginally significant, too (see Fig. 4(c), $t(7) = 1.4$, $p = 0.10$). Thus, it is suggested that α might be improved by RAS gait training.

Finally, the training effect about Silent Control gait training was analyzed (see Fig. 5). The length of each individual trajectory was likely to be smaller than that of WM gait training or that of RAS gait training (see Fig. 5(a)). Also, the directions of individual trajectories were not unified. In truth, there was no significant difference of *CV* between pre-training and post-training in Silent Control gait training (see Fig. 5(b), $t(7) = -0.17$, $p = 0.87$). In addition, the α in post-training was not significantly different from that of pre-training (see Fig. 5(c), $t(7) = -0.71$, $p = 0.50$). From these results, the training effect of Silent Control gait training is not likely to be unified.

B. Comparison of training effect between 3 groups

Table 1 shows the characteristics of the participants in each group. The median of HY, sex ratio, average of age or disease duration in each group are not different between 3 types of training (Levene's test: $F(2,21)=2.3$, $p=0.13$ for age, $F(2,21)=0.7$, $p=0.49$ for duration disease, $F(2,21)=0.7$, $p=0.49$ for HY.; ANOVA: $F(2,21)=0.4$, $p=0.67$ for age, $F(2,21)=1.0$, $p=0.38$ for duration disease, $F(2,21)=0.2$, $p=0.86$ for HY).

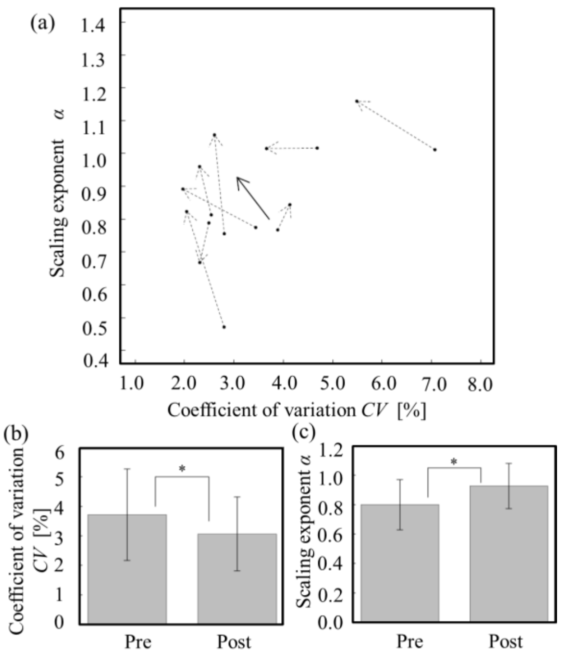

Fig. 3. Result of WM gait training. (a) Trajectory on *CV*-*α* plane about WM gait training. Dashed arrows are individual trajectory, and solid arrow is the averaged trajectory. WM gait training tends to increase *α*, and decrease *CV*. (b) Effect of WM gait training on *CV*. The significant difference of *CV* between pre-WM gait training and post-WM gait training was observed (*: $p \leqq 0.05$). (c) Effect of WM gait training on *α*. The significant difference of *α* between pre-WM gait training and post-WM gait training was observed (*: $p \leqq 0.05$).

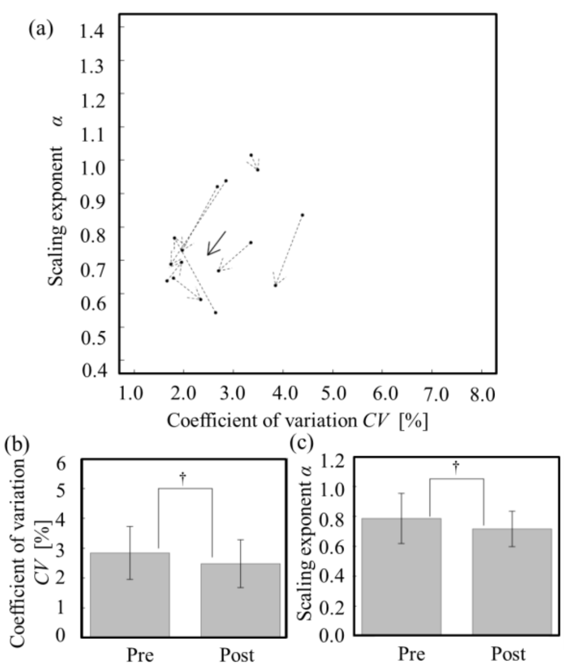

Fig. 4. Result of RAS gait training. (a) Trajectory on *CV*-*α* plane about RAS gait training. Dashed arrows are individual trajectory, and solid arrow is the averaged trajectory. (b) Effect of RAS gait training on *CV*. The difference of *CV* between pre-RAS and post-RAS was marginally significant († : $p \leqq 0.10$). (c) Effect of RAS gait training on *α*. The difference of *α* between pre-RAS gait training and post-RAS gait training was marginally significant († : $p \leqq 0.10$).

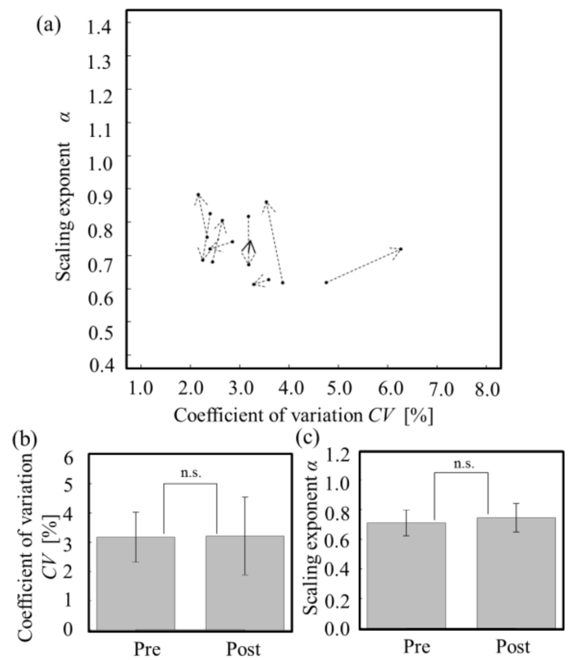

Fig. 5. Result of Silent Control gait training. (a) Trajectory on *CV*-*α* plane about Silent Control gait training. Dashed arrows are individual trajectory, and solid arrow is the averaged trajectory. (b) Effect of Silent Control gait training on *CV*. The difference of *CV* between pre-training and post-training was not significant. (c) Effect of Silent Control gait training on *α*. The difference of *α* between pre-training and post-training was not significant (n.s.).

In addition, the homogeneity of *CV* and *α* in pre-training among 3 types of gait training was confirmed (Levene's test: $F(2,21)=1.2$, $p=0.33$ for *CV*, $F(2,21)=1.2$, $p=0.31$ for *α*). Significant difference of *CV* and *α* in pre-training among 3 groups were not observed (ANOVA: $F(2,21)=0.4$, $p=0.67$ for *CV*, $F(2,21)=1.0$, $p=0.38$ for *α*).

Fig. 6 shows the results of the comparison of training effect on *CV*-*α* plane between interactive WM gait training, fixed-tempo RAS gait training and Silent Control gait training. The averaged trajectories of 3 gait trainings were plotted on the *CV*-*α* plane in Fig. 6(a). The solid arrow is the averaged trajectory of WM gait training, the alternate long and short dashed arrow is the averaged trajectory of RAS gait training and the dashed arrow is the averaged trajectory of Silent Control gait training. The length of averaged trajectory about WM gait training is the longest among three types of training.

We compared the change amount of *CV* to understand the effect of training type on *CV* (see Fig. 6(b)). At first, the homogeneity of variance was confirmed ($F(2, 21) = 0.40$, $p = 0.67$). ANOVA showed the weak trend of difference among 3 groups ($F(2, 21) = 2.5$, $p = 0.11$). As a supplement, marginal significant difference between WM gait training and Silent Control gait training was shown by Tukey test ($p = 0.09$).

TABLE I

CHARACTERISTIC OF PARTICIPANTS (MEDIAN OF HY; AVERAGE OF AGE, DISEASE DURATION, CV AND α IN PRE- AND POST-TRAINING)

Group (Male: female)	Median of HY (range)	Mean (SD) of age [year]	Mean (SD) of duration disease [year]	Pre-training		Post-training	
				Mean (SD) of CV [%]	Mean (SD) of α	Mean (SD) of CV [%]	Mean (SD) of α
WM (4:4)	2.75 (2-3)	69.9 (12.4)	7.3 (5.5)	3.7 (1.6)	0.8 (0.17)	3.1 (1.3)	0.93 (0.15)
RAS (4:4)	2.25 (1.5-3)	69.1 (7.7)	5.4 (2.5)	2.8 (0.9)	0.79 (0.17)	2.5 (0.8)	0.72 (0.12)
Silent Control (5:3)	2.5 (2-3)	70.4 (4.6)	5.5 (3.7)	3.2 (0.9)	0.71 (0.09)	3.2 (1.3)	0.74 (0.1)
p value	0.19	0.96	0.61	0.5	0.2	0.62	0.04

On the other hand, to analyze the effect of training type on α, the change amount of α was compared among 3 trainings (see Fig. 6(c)). Using Levene's test, the null hypothesis of homogeneity of variance was not rejected ($F(2, 21) = 0.01$, $p = 0.99$). An ANO VA on the change amount of α yielded significant variation among training conditions ($F(2, 21) = 3.5$, $p = 0.05$). A post-hoc Tukey's HSD test showed that WM gait training groups and RAS gait training groups differed significantly at $p < 0.05$ ($p = 0.03$). The Silent Control gait training group was not significantly different from the other two groups, lying somewhere in the middle.

I. DISCUSSION

In this study, we proposed rhythm-fluctuation-based evaluation platform for gait training. The rhythm-fluctuation-based evaluation platform is constructed by the combination of CV and α of stride interval. In interactive WM gait training, CV decreased and α increased significantly, and these changes represent the improvement of gait rhythm generation. By fixed-tempo RAS gait training, CV was likely to be decreased, but α tended to be decreased. However, in Silent Control gait training, the CV and α were not significantly different between pre-training and post-training. From these results, only interactive WM gait training shows significant positive effect on both of CV and α. The decrease of amplitude of gait rhythm fluctuation in hemiplegic patients was reported [4], [5], but that in PD patients were not mainly reported in previous studies about WM gait training [10], [11].

In addition, to compare the training effect between 3 groups, the change amount of CV and that of α from pre-training to post-training were analyzed. The significant difference of α between WM gait training and RAS gait training was shown. In the previous study, Hove *et al*. reported the carry-over effect on α of PD patients in 5 minutes after the WM gait training trial [10]. The training period and the evaluated time point after the gait training in this study are longer than previous study [10]. Uchitomi *et al*. [11] compared the trend of day-by-day change amount of α and that of CV, and the amount in previous study [11] is smaller than this study.

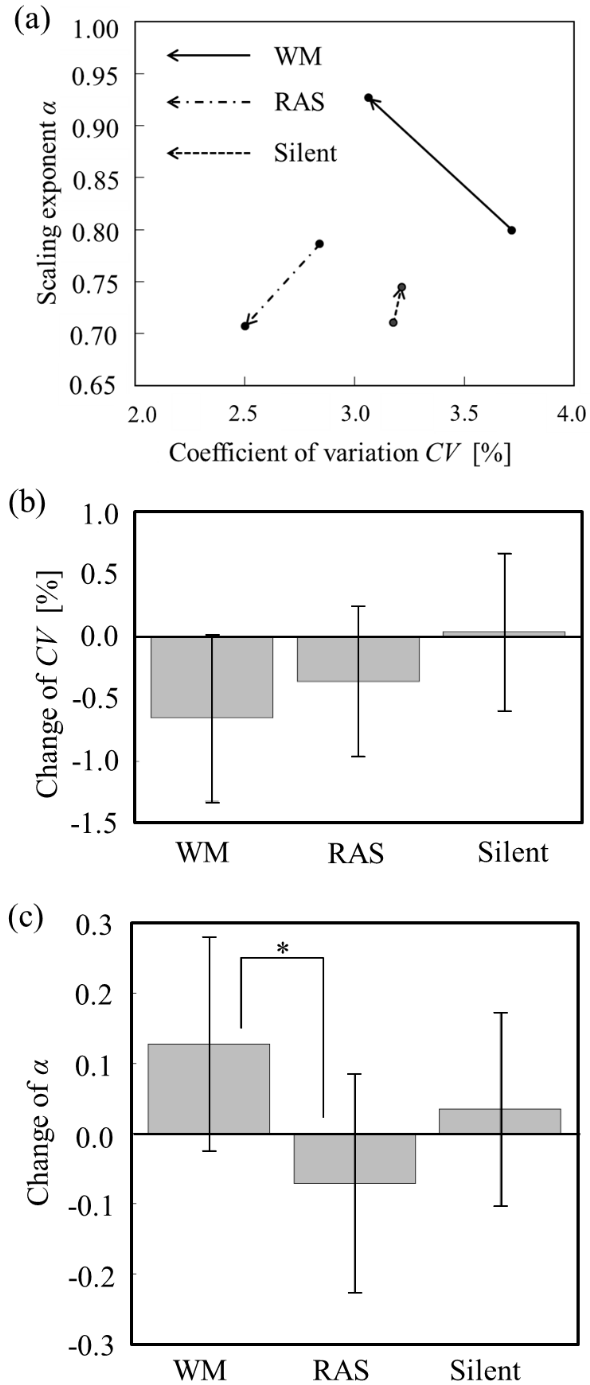

Fig. 6. Comparison of training effect on rhythm-fluctuation-based evaluation platform between three training conditions. (a) Averaged trajectory on CV-α plane of three trainings. WM decrease CV and increase α. However, RAS decrease both of CV and α. (b) Training effect on coefficient of variation CV between three training conditions. There was no significant difference between each training conditions. (c) Comparison of training effect on scaling exponent α between three training conditions. The significant difference between WM and RAS was observed (* : $p \leqq 0.05$).

The rhythm-fluctuation-based evaluation platform was defined as the combination of *CV* and α in previous study [12]. The *CV* indicates amplitude of gait rhythm fluctuation, one of the measures of gait stability, and this is associated to symptom of PD [13], [18], such as festinating gait, and freezing of gait [19]. In previous study, the presence or absence of PRD is mainly differentiated by *CV* [12]. The α represents fluctuation property of gait rhythm, and this is related to neurodegenerative disease [9], [12], [20]. Especially, the severity of PRD seen in PD patients was mainly discriminated by α [12]. The improvement by gait training on this evaluation platform have potential to estimate the recovery of severity of PD. Gait training is based on human gait rhythm generation property. From aspect of movement generation, the movement variability is very important [21]. *CV* is linear indicator of variability and it represents the static property of gait rhythm generation. The *CV* can evaluate abnormality of neural rhythm generation in views of sustaining their own rhythm. On the other hand, α is nonlinear indicator of variability and it represents the dynamic property of gait rhythm generation. The α can evaluate alteration of neural rhythm generation from aspect of ability to adapt themselves to environment. These indicators would be able to evaluate complemental aspects of gait rhythm generation.

From this study, the difference between interactive rhythmic gait training and unidirectional rhythmic gait training were shown in rhythm-fluctuation-based evaluation platform. In the future, the mechanism of improvement through interactive rhythmic gait rehabilitation is expected to be investigated.

II. Conclusion

The 3 types of gait training were evaluated by rhythm-fluctuation-based evaluation platform, which is the combination of *CV* and α of stride interval. The effect of 4-day gait training was quantified by the change amount of *CV* or α to compare the effect and the change direction between interactive WM, fixed-tempo RAS and Silent Control gait training. As a result, the rhythm-fluctuation-based evaluation platform was shown to be applied to evaluate gait training. In addition, the difference of the training effect between the interactive WM gait training and fixed-tempo RAS training were clearly detected.

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