2012 IEEE/SICE International Symposium on System Integration (SII)
Kyushu University, Fukuoka, Japan
December 16-18, 2012

Effect of interpersonal synchrony on gait fluctuation characteristics: an analysis of synchronization gait assist system

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Abstract— **In a walking rehabilitation, the cooperative walking between therapist and patient is implemented and the synchrony of walking rhythm is often observed. So, we suggest that the interpersonal synchrony is important for walking rehabilitation. Our group has proposed gait assistive system using interactive rhythmic auditory stimulation to emulate interpersonal synchrony. It is called "Walk-Mate". In the previous study, the improvement effects of walking with the fixed-tempo Rhythmic Auditory Stimulation (RAS) and Walk-Mate were compared. As a result, walking with Walk-Mate had 1/f structure and was more effective than walking with RAS.**

In this study, the emulated interpersonal cooperative walking between human and auditory stimulation was analyzed to investigate the relationship between synchrony and gait improvement effect. Fixed-tempo RAS were compared to Walk-Mate. Twenty PD patients and 18 younger healthy persons were participated in experiments. We showed that the phase difference with Walk-Mate was less variable and more temporally-stable than with RAS. It meant the walking with Walk-Mate has the higher synchrony than with RAS. The combination of the result and previous result indicates that the synchrony between participants and auditory stimulation were related to the gait dynamics of participants' stride time. In addition, the PD patients showed the lower synchrony than young healthy people. Therefore, we suggest that it is necessary that the auditory system encourage them to synchronize. We suggested the importance of considering the synchrony in rehabilitation for PD patients.

I. Introduction

There is potential that interpersonal interactions are necessary for human development. Piaget [1] suggested that interpersonal interactions are related to the development of the infant's cognitive functions. Castelfranch *et al.*[2] focused on the interactive process between a handicapped person and there therapist in rehabilitation, and suggest that cooperative movements contribute to successful rehabilitation. In a walking rehabilitation, cooperative walking between therapist and patient is implemented. On this occasion, the synchrony of walking rhythm between therapist and patient is often observed. So, we hypothesized that the synchrony is important in the rehabilitation of rhythmic movement.

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So, we study the rehabilitation system encouraging patients to synchronize and propose the interactive "Walk-Mate" system [3]. The model of the human cooperative walking was implemented in Walk-Mate system. The system outputs the auditory stimulation in place of the virtual robot's footstep. The virtual robot's stride time changes dynamically based on measured human steps and makes it possible to mutually entrain. So, each rhythm can interactively approach. It was showed that the interactive Walk-Mate system can improve gait rhythm of hemiparetic patients [4] and reduce gait festination in the Parkinson's disease (PD) patients [5].

On the other hands, as a method of rehabilitation using sound in PD patients for gait disturbance, walking with fixed-tempo Rhythmic Auditory Stimulation (RAS) is attracted attention. In the fixed tempo RAS condition, the human gait rhythm approach to RAS's tempo not interactively but one-sidedly. It was reported that fixed-tempo RAS can increase gait tempo and stride length [6] and decrease the magnitude of stride-time variability [7,8].

Hove *et al.*[9] compared the fractal scaling with RAS condition and Walk-Mate condition. Hausdorff *et al.* showed that the distribution of stride times in a healthy walk has a 1/f-like structure similar to the fractal-like long-range correlations [10, 11] and in PD, the fluctuations are relatively random (white noise) [10]. So, Hove *et al.* assessed and compared effectiveness of treatments using Detrended Fluctuation Analysis (DFA) on the basis of the previous study [10,11] and reported that Walk-Mate was more effective than RAS. However, it is necessary to clarify the reason for resulting in different improvement effects, adequately.

Therefore, we aimed at analyzing the synchrony and making a study of relationship between synchrony and improvement effects on fluctuation. We focused on the phase relation between human gait and auditory stimulation and made an index of synchrony. We compared two auditory stimulation methods using the index and related the result to the previous result [9].

II. Data Description

In this study, we carried out the further investigation into data analyze gait data of previous study [9]. Accordingly, we summarize the experimented method and this result.

A. Participants

Twenty patients (12women, 8 men) with idiopathic Parkinson's Disease participated in the experiment (mean age= 69.2 years; SD =7.7). Patients' disease severity was

Hoehn and Yahr Stage 2–3. Eighteen healthy controls (16 men) also participated (mean age = 24.7 years; SD= 2.7). All participants were able to walk without sticks and mobility aids.

B. Experimental procedure

Participants were instructed to walk at a natural and comfortable pace around a corridor at a distance of about 200 meters.

Gait timing information was collected via pressure sensors attached to participants' shoes. Rhythmic auditory stimuli (100 ms sine tones at 523 Hz and 700 Hz) were played over circumaural headphones. There are three experimented conditions in auditory stimulation: interactive rhythmic cueing with period and phase adjustment (''Walk-Mate''); fixed-tempo rhythmic auditory stimulation (''RAS''); and unassisted silent control condition (''Silent Control''). For the PD patients, each block consisted of three separate trials: first, a pretest trial without auditory stimulation to establish baseline performance; second, a test trial with one of the three auditory stimulation conditions to establish the immediate efficacy of stimulation; and third, a post-test trial without auditory stimulation. Trials within a block were separated by 5-minute breaks, and blocks were separated by 30-minute breaks to eliminate the effects of fatigue due to the previous trial. The healthy control experiment omitted the baseline and carry-over trials. In trials with auditory stimulation, the rhythmic auditory presentation started after 20 seconds of walking.

C. Auditory stimulation condition

1) Walk-Mate: Schematic depiction of the Walk-Mate system is shown in Fig.1(a). Walk-Mate system implements interpersonal cooperative walking to share the walking rhythm between a human and virtual robot [3]. The rhythm control system was organized hierarchically in two modules (Fig.1(b)).

Module 1 mutually entrained the frequencies of the computer's auditory outputs and the participant's strides. This module was consisted based on "mutual entrainment" model using phase oscillators [3][12]. Its control method is shown in (1). Here, $\omega_m$designates computer system's natural frequency and θ_m represents its phase. The input variable of this equation, θ_h, presents the phase of the participant's gait cycle. K_m (> 0) designates the coupling constant.

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

Module 2 was responsible for adjusting the phase difference to a target value. The relative phase between the human's step time and virtual robot's step time(the computer system's auditory output from module 1) is $\Delta\theta_m = \theta_h - \theta_m$. The control law for Module 2 was presented as in (2), in which $\Delta\theta_m$, $\Delta\theta_d$, and μ represent the Module 1 phase difference, the target phase difference, and the control gain, respectively.

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

Hove *et al.* [10] set $\Delta\theta_d = +0.2$rad, which means that auditory output timing is little later than human's step timing. And, they set $K_m = 0.5$ and $\mu = 0.32$.

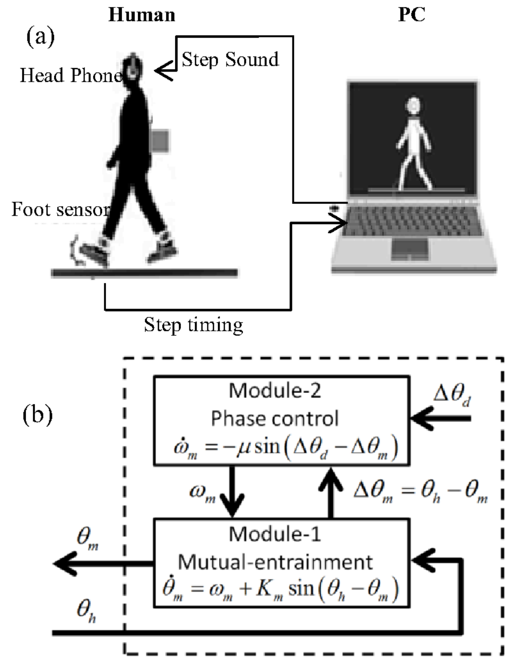

Fig. 1. Walk-Mate overview(a) Schematic depiction of the WalkMate system.(b) the control model for interpersonal cooperative walking. system was organized hierarchically in two modules.

2) Rhythmic Auditory Stimulation (RAS): In the RAS condition, remained constant throughout the trial. Setting the stimulus tempo to the participant's natural tempo, stimulus tempo was determined based on the mean of initial 5 step periods after excluding extreme values.

D. Analysis of the experiment in the previous studies

Hove *et al.* [9] used Detrended Fluctuation Analysis (DFA) [13] to analyze fluctuation of stride time. DFA calculates the scaling exponent α. Using DFA, they evaluate fluctuation property of the original gait time-series. Using DFA, a scaling exponent $\alpha \approx 0.5$ corresponds to unpredictable white noise; $\alpha \approx 1.0$ corresponds to 1/f like noise and long-range correlations. Younger healthy person's walking showed $\alpha \approx 1.0$ and PD patient's walking showed $\alpha \approx 0.5$ [10].

Hove *et al.* [9] was reported that the stride time DFA fractal-scaling exponent for Parkinson's patients was lower than for healthy participants and in the PD, Walk-Mate auditory stimulation conduced to higher fractal scaling compared to no auditory stimulation and RAS conditions . In addition, there is no difference between PD with Walk-Mate condition and healthy participants' normal walking (Fig.2).

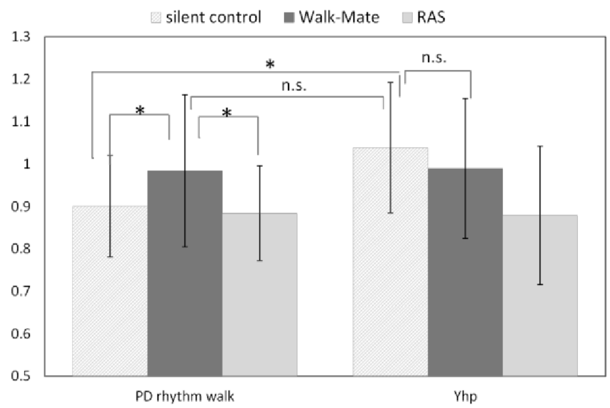

Fig. 2. averaged DFA fractal- scaling exponent of gait cycle time series in PD patients and younger healthy people (Yhp) [10]. The cueing condition are unassisted Silent control; interactive Walk-Mate condition; and fixed tempo RAS condition .p<.05; n.s.=non-significant.

III. Method of Analysis

In this study, analyzed data are measured in test trials with "Walk-Mate" condition and fixed tempo "RAS" condition.

We tried to evaluate the synchrony between human steps and auditory stimulation. We analyzed time variation of their phase difference. The phase difference is calculated according to phase oscillators which constitute walking control model. The phase difference is defined as in (3).

$$\Delta\theta(j) = \theta_h\big(t(j)\big) - \theta_m\big(t(j)\big), \tag{3}$$

where, $\Delta\theta(j)$ represents the j-th phase difference. $t(j)$ represents time when j-th human step. It is when $\theta_h = 0$. $\theta_h(t)$ and $\theta_m(t)$ denote human step's phase and auditory stimulation's phase, respectively. If auditory stimulation is produced later than human step's timing, the phase difference is positive value.

We use the standard deviation of the phase difference ($PdSD$) as a measure of the synchrony. If the standard deviation is small, then it indicates that the phase relationship between human steps and auditory stimulation is maintained. We defined small standard deviation as it is a state of high synchrony. The standard deviation is shown as (4).

$$PdSD = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(\Delta\theta(j) - \overline{\Delta\theta(j)}\right)^2} \tag{4}$$

IV. Result

Fig.3 shows examples of time series data of phase differences with Walk-Mate condition and the fixed tempo RAS condition. The phase difference was fixed within a small range and the variability of phase difference is small (Fig.2(b)).In the Walk-Mate condition, it was showed that the synchrony between human steps and auditory stimuli was high. In the RAS condition, the phase difference varied considerably with time (Fig.2(a)). Fig.4 shows the averaged standard deviation of phase difference (*PdSD*) of two auditory stimuli. We applied ANOVA to the analyzed *PdSD*.

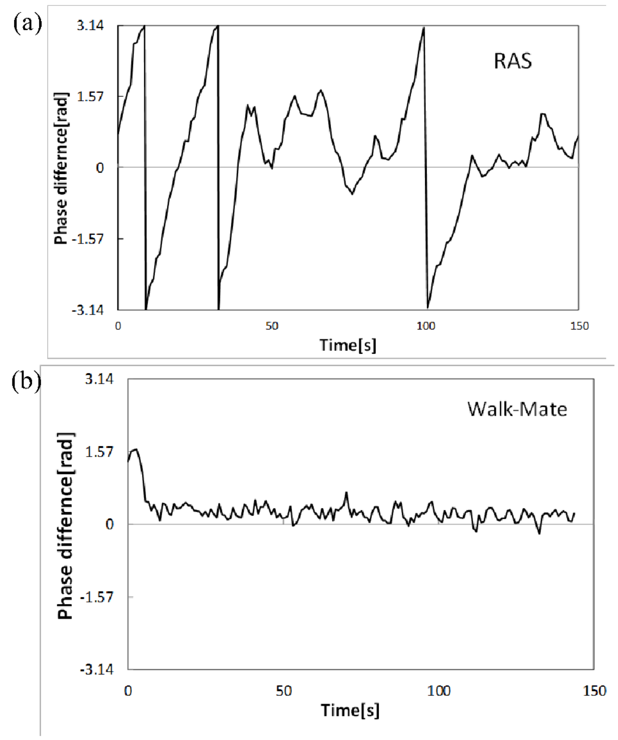

Fig. 3. Time series of Phase difference, (a)RAS condition: the phase difference changes enormously with time, (b)Walk-Mate condition: it is fixed within the small range and the phase difference is stable.

The *PdSD* in the Walk-Mate condition for all subjects was significantly lower than in the RAS condition (F(1,70)=645.3, p<.01). In the addition, we applied two-sided t-teat. For a similar difference between Walk-Mate condition and RAS condition was also observed in the group of PD patients (t(19)= 63.5, p<.01). By definition, Walk-Mate condition had the higher synchrony than RAS condition.

In the Walk-Mate condition, The *PdSD* in the PD patients was higher than in the young healthy person (t(36)= 62.5, p<.05)and in the RAS condition , a marginal significance was observed between PD patients and young healthy persons. (t(36)= 1.73, p=.10)

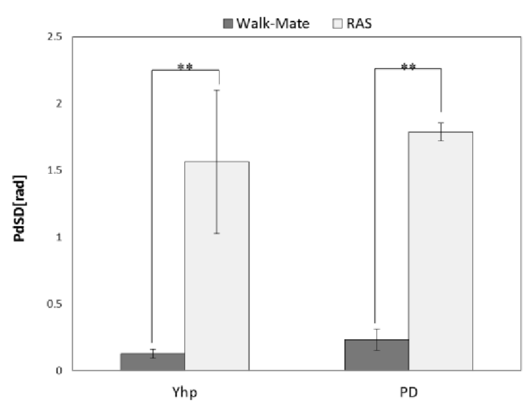

Fig. 4. The interpersonal mean value of standard deviation of the phase difference (*PdSD*) of younger healthy people and PD patients were compared.For each subject groups, *PdSD* in the Walk-Mate condition was significantly lower than in the RAS condition (**:p<.01)

V. Discussion

In this study, we further analyzed the gait data observed in the previous study [9]. We evaluated the synchrony between human steps and auditory stimulation using the *PdSD*.

In the interactive Walk-Mate condition, variation of the phase difference between timing of human steps and timing of stimulus was small. The other way, in the fixed tempo RAS condition, tendency which the phase difference varied enormously was verified a lot. This means that gait in the Walk-Mate has a higher synchrony than RAS condition.

Hove *et al*. [9] analyzed the gait dynamics of PD patients. They reported that the Walk-Mate system improved the fractal scaling than unassisted Silent Control and RAS. From the previous result and our result of analysis, we suggest that the synchrony between human step's timing and auditory stimulation has a relationship with improvement effects of gait dynamics for PD patients.

The rhythm of RAS was determined based on the individual's stride time. Therefore, it is expected that they can synchronize with the fixed tempo RAS, but they didn't particularly synchronize. We suggest that the difference in the method of generating the rhythm causes difference of the result between Walk- Mate and RAS. RAS doesn't interact with a human walking and outputs fixed paced auditory stimulation. So, in order to synchronize, it is necessary that human tries to synchronize to sound unilaterally. In the result, human is too much to handle tiny declinations of the phase and the declination is accumulated. On the other hands, Walk-Mate mutually interacts with human gait and changes stride time dynamically. Hence, the rhythm of human gait and auditory stimuli come close interactively and human can synchronize with Walk-Mate auditory stimulation, easily.

In addition, we compared the group of subjects. The *PdSD* in PD patients were higher than in young healthy person in each auditory condition. At the result, we suggest that it is difficult for PD patients to synchronize with auditory stimulation and it is necessary that the system encourages them to synchronize to compensate lack of synchronization. However, Hausdorff *et al*[14] demonstrated that stride interval fluctuations are less correlated in elderly subjects. Therefore, it is possible that influences other than disease contributed to group differences. We should make comparison between PD patients and elderly subjects .

We focused on the interpersonal synchronization for walking. Meanwhile in the previous study, the intrapersonal synchronization was also investigated. It was indicated that arm swing is naturally coordinated with the legs for walking, however, decreased synchronization of leg and arm movements has been reported onset of PD [15][16] and Muto *et al.*[17] analyzed a connection between interpersonal automatic motor control and intrapersonal voluntary control in corporative walk. Thus, we need to consider the intrapersonal synchronization and investigate the relationship between interpersonal synchrony and intrapersonal synchrony.

Acknowledgment

M.J Hove and K.Suzuki offered the gait data to us. We are deeply grateful to them.

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