Proceedings of the 2011 IEEE/ICME
International Conference on Complex Medical Engineering
May 22 - 25, Harbin, China

Interpersonal Synchrony-based Dynamic Stabilization in Walking Rhythm of Parkinson's Disease

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Abstract **- Considerable research attention has been devoted to interpersonal synchrony and to locomotor control. However their intersection, the interpersonal synchronization of stepping rhythms which is widely observed in our daily life, remains relatively unexplored, despite being a common phenomenon that has considerable rehabilitation potential. Therefore, from the perspective of mutual entrainment of gait rhythms, we have constructed an interpersonal synchrony emulation system between a human subject and a virtual biped robot that generates pacing signals using nonlinear oscillators. This system synchronizes the gait cycles of a human and the robot in a cross-feedback manner, by presenting auditory stimuli that indicate the timing of the partner's foot contacting the ground. Here, we evaluated the effectiveness of this mutual synchrony model in gait stabilization of two Parkinson's disease patients, who display disturbances in rhythm formation and gait festination (accelerating steps). The results showed that the gait festination, as measured as stride time reduction rate, stabilized and accelerated less compared to unassisted walking (i.e., not exposed to the auditory stimuli). In addition, carry-over effects were observed. After termination of the auditory stimuli, the gait remained stabilized. This is the first study using mutual entrainment in dynamically stabilizing gait festination. These results seem to warrant future clinical application of this interpersonal synchrony emulation system for patients with a variety of motor disorders.**

Index Terms - Parkinson's disease, Gait festination, Stride time, synchronization, Walk-Mate.

I. INTRODUCTION

Parkinson's disease (PD) is one of the neurodegenerative diseases in substantia nigra. This disease decreases dopamine in the basal ganglia, causing dysfunction of the basal ganglia and their associated networks. PD patients have difficulty starting, stopping, or sustaining movement. Rhythm generation and the timing of repeating movements are also disturbed in PD[1], [2]. These disturbances are related to the disorders of the basal ganglia and the projection path from the brainstem to the spinal cord[3]–[6]. For example, PD scrambles gait rhythm, gait cycle, and gait pattern of the patient[7]–[9].

PD is treated with not only dopaminergic medication and deep brain stimulation, but also behavioral therapy. Behavioral therapy is one of the rehabilitation methods. This is applied to the PD patients of various levels because this is the cure without medicament or surgery. In behavioral therapy for gait disorder, there are mainly two methods. One is Rhythmic Auditory Stimulation (RAS). The other is Walk-Mate.

RAS is the method with the rhythmic sounds having the fixed tempo in order to improve gait disorder. In this method, a patient makes an effort to synchronize one's own gait rhythm and rhythmic sounds. Previous studies reported that RAS improved stride lengths, gait cycles, walking speeds, or gait patterns of PD patients[10]–[13].

On the other hand, our research group has focused on interpersonal synchrony. In daily life, we have often experienced synchronizing our rhythm or our timing with someone. Hence, it seems that there is interactive component of rhythm behind interpersonal synchronization. For example, Muto et al. suggested that it was important for gait rehabilitation to implement mutual interaction between a caregiver and a patient with gait disorder[14].

Moreover, our previous studies modeled the phenomenon of mutual interaction and developed the biped virtual robot of interpersonal synchrony emulation system. The robot was named Walk-Mate[19]–[22]. Walk-Mate makes patient's gait rhythm and rhythmic sounds interact. This interpersonal synchrony emulation system stabilized PD patients' gait through the mutual entrainment between those two rhythms.

In addition, our previous study compared the influences of Walk-Mate and RAS on Parkinson's gait by using a common evaluation method[16]. In this study, gait cycle fluctuation was focused on as the index of dynamic stability of a gait. The fluctuation was analyzed by fractal scaling exponent that was one of the index for evaluating 1/f characteristics from the viewpoint of dynamics. As a result, Walk-Mate interactive

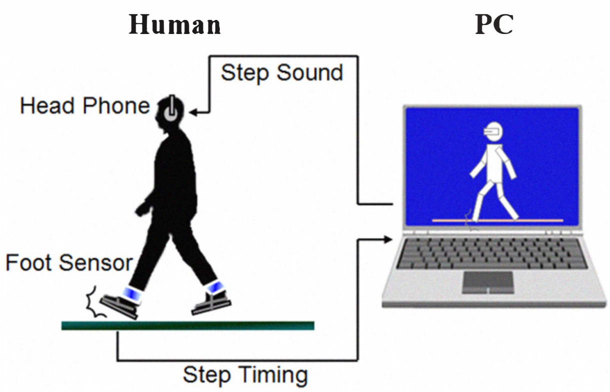

Fig. 1. The exchange of footstep sounds between a human walker and a walking robot.

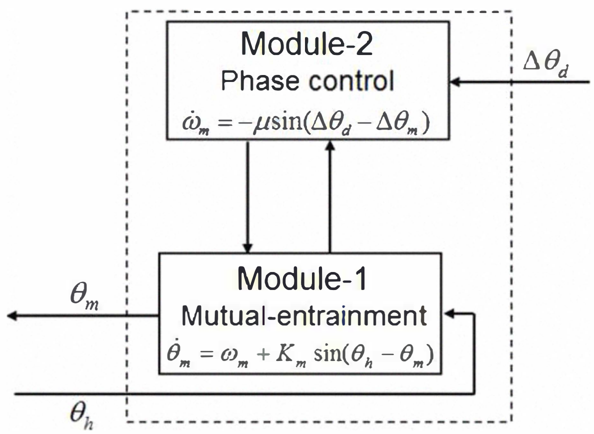

Fig. 2. The rhythm generator model in the robot had a hierarchical structure

rhythmic stimulation dynamically stabilized Parkinson's gait more than fixed-tempo RAS. Thus, the study suggests that the interactive component is important to improve the dynamic stability of gait with PD.

From these background, we focuses on the dynamic destabilization that occurs in a common Parkinsonian gait disorder: festinating or accelerating gait[6], [15]. Festination is an alteration in gait pattern characterized by a quickening and shortening of normal strides. We expect that Walk-Mate has potential for mitigating festination by dynamically stabilizing gait. Therefore, the aim of this study is to investigate the effectiveness on mitigating festination by applying the function which Walk-Mate generates of the dynamical stabilization of gait.

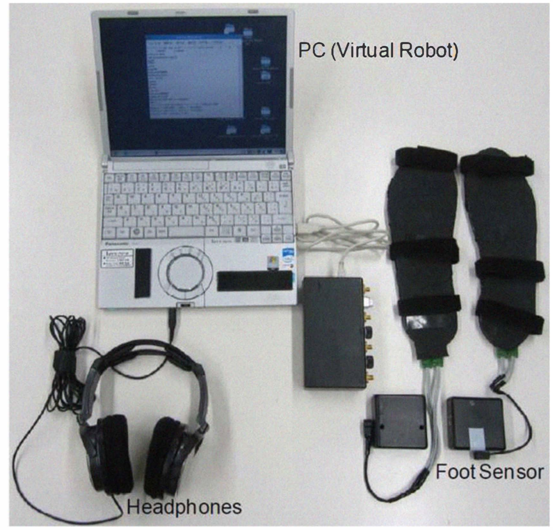

Fig. 3. Experimental device.

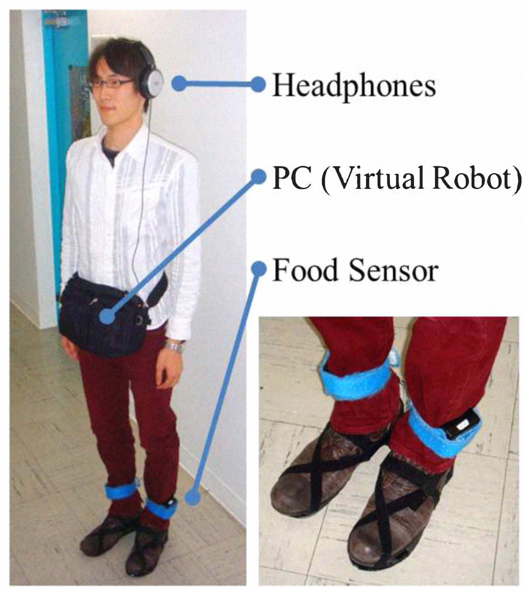

Fig. 4. Experimental setup.

II. Material and Method

A. Interpersonal synchrony emulation system

As shown in Figure 1, the interpersonal synchrony emulation system included a cross-feedback process, whereby the virtual robot's timing of ground contact was given as an input signal to the subject, while the robot was provided with the subject's heel strike timing. The rhythm generator model in

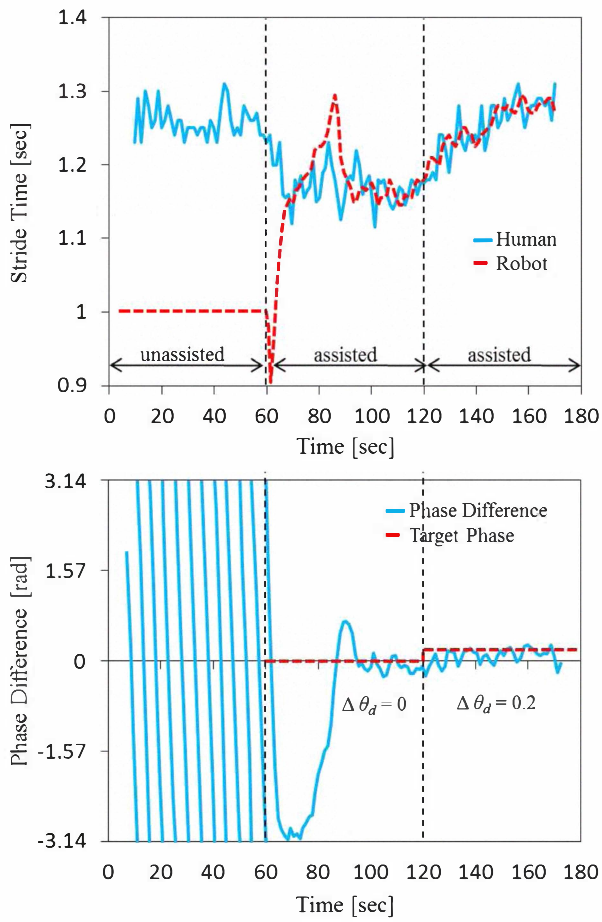

Fig. 5. An example of time-course changes in the stride time and phase difference of a healthy subject, achieved by the interpersonal synchrony emulation system.

the robot had a hierarchical structure, as illustrated in Figure 2. Module 1 was responsible for mutual entrainment between the human stepping rhythms and the virtual robot's gait pattern, and Module 2 controlled the phase difference (shift in timing) between the sensory input (the subject's foot contact with the ground) and the motor output (production of robot footstep sound stimuli to the subject) to a targeted value. More specifically, Module 1 involved the use of a phase oscillator[18], which has been shown to be effective for simulating CPGs[23], and Module 2 implemented feedback control for the difference (phase difference) in the timing of input and output of Module 1. See appendices A, B, and C for more detailed description of rhythm generator model in the interpersonal synchrony emulation system.

The relevance of this model is supported by the finding that human locomotor behaviors were hierarchically governed by spinal CPG-dependent rhythm modulation and by cerebellar and brainstem feedback control systems[25], [26]. It was further supported by the dual process model[27] and our experimental results in synchronization tapping[28],[29]. Figure 3 provides an overview of the complete gait support system, including the portable PC and other devices, as well as a subject wearing this system (Figure 4).

Figure 5 shows an example of time-course changes in the stride time and phase difference achieved by this system. First, a healthy subject was instructed to walk down a straight corridor. The subject walked without exposure to the tones in the first 60 seconds, followed by another 60 seconds during which the cross-feedback of the walking signals was conducted with a targeted phase difference of 0 rad, followed by another 60 seconds interval during which the gaits were synchronized with the targeted phase shift of 0.2 rad (a slight delay in presentation of the auditory stimuli relative to the time point of the subject's heel strike).

During the unassisted walking condition (0-60 sec), the subject and the virtual robot walked at different stride time. During the assisted walking condition (60-120 sec), their stride time drew closer to each other via mutual entrainment, with the phase difference stably converging to the target value of 0 rad. During the condition when the target phase difference was set to 0.2 rad (120-180 sec), the subjects' walking slowed down; their stride times increased automatically without being aware of the phase difference.

This phenomenon is thought to be useful to stabilize gait festination of PD. These results showed that the gait cycle could be manipulated by controlling the target phase difference in mutual synchrony.

B. *Participants*

Two normal-hearing and non-demented patients with PD were recruited. Table I shows the subjects' age, sex, disease duration, modified Hoehn and Yahr stage (modified HY), and Unified Parkinson's Disease Rating Scale (UPDRS).

They exhibited gait festination during a prescreening interview with the physician, and were receiving medication for treatment of PD. Their Hoehn and Yahr stages (severity indicator, range: 0-5) were 2 or 3, indicating independent ambulation. All subjects provided written informed consent before participation.

TABLE I
LIST OF PARKINSON'S DISEASE PATIENTS

Subject No.	Age	Sex	Disease duration	Modified HY	UPDRS part 2	UPDRS part 3
1	92	Male	2	3	22	29
2	77	Male	2	2	7	14

C. *Task*

Subjects were instructed to walk along the path in the corridor; at predefined intervals, they were exposed to rhythmic tones presented by the interpersonal synchrony emulation system, which they were carrying. The corridor was flat and straight, with the ambient temperature and light intensity adjusted to the comfort of the subjects. The walking distance was set at 80 m. Subjects were instructed to make a pretest walk for 80 m to familiarize with the system and environment, without presentation of rhythmic sound stimuli (unassisted condition). Then, after a 5 minutes rest, they were given the following task. One round of the 80 m walking task included a sequence of unassisted walk, synchronized walk (with presentation of step-guiding tones), and unassisted walk. This study was approved by the Kanto Central Hospital Ethics Committee.

D. *Experimental setup*

In specific terms, the timing of the virtual robot's ground contact was presented to the subject as an auditory stimulus (combination of F5 and C5 notes, 200 ms duration) via headphone (HP-RX500, Victor, Japan). The subject's footground contact was detected by a pressure sensor (OT-21BPG, Ojiden, Japan) fixed underneath the shoe. The detected signals were transmitted to the gait simulation software program running on a portable PC (CF-W5, Panasonic, Japan). The measurement, calculation, and recording of the heel strike timing were performed in real time at 10 ms intervals. The Walk-Mate system was intended to achieve interpersonal gait synchrony between the subject and the virtual bipedal robot.

E. *Analysis of gait cycle and phase difference*

In order to evaluate the gait festination, we focused on human stride time as the gait cycle. The human stride time (gait cycle time), T_h, is shown in equation (1), in which T_h is defined as the difference between the ground-contact timing $t_h(i+1)$ for the *(i+1)-th* step and $t_h(i)$ for the *i-th* step of the same leg. Equation (1) is applicable to the virtual robot as well, by replacing the suffix h (for human) with m (for robot).

$$T_h(i) = t_h(i+1) - t_h(i). \qquad (1)$$

Here, the subject's phase difference $\Delta h(i)$ for the *i-th* step is determined based on the difference between $t_h(i)$ (i.e., the time at which the subject's foot makes the *i-th* ground contact) and tm(i) (i.e., the time at which the auditory stimulus is presented in response to the *i-th* ground contact), as shown in equation (2). In this equation, $t_m(i)$, which is defined as the time at which the virtual robot makes the *i-th* ground contact, provides the time at which the auditory stimulus is provided to the subject, because these timings are identical. This equation may also be understood to indicate the phase difference between the times at which the subject and the virtual robot make the i-th ground contact.

$$\Delta\theta_h(i) = \left(t_h(i) - t_m(i)\right)\frac{2\pi}{T_h(i)}. \qquad (2)$$

F. *Quantification of gait festination*

Gait festination refers to a clinical manifestation in which both the stride time and the stride length decrease over time during walking. In this study, we paid attention to stride time decrease and conducted least-squares linear regression analysis to estimate the temporal change in stride time; the gradient of the regression line, α, was used to evaluate the stride time reduction rate. The gradient, α, which is calculated by equation (3), relates to decrease in stride time per second. In this analysis, based on preliminary analysis results (mean ± SD of α: 0.00002 ± 0.00049) obtained from 10 healthy subjects (7 males and 3 females, mean age: 25.6 years) under the same experimental conditions, we defined gait festination as $\alpha < -0.001$.

$$\alpha = \frac{n\sum_{i=1}^{n} t_h(i)T_h(i) - \sum_{i=1}^{n} t_h(i)\sum_{i=1}^{n} T_h(i)}{n\sum_{i=1}^{n} t_h(i)^2 - \left(\sum_{i=1}^{n} t_h(i)\right)^2}. \qquad (3)$$

III. RESULT

Figure 6 provides time-course changes in stride time and phase difference in subject No.1 equipped with the system. In the first 40 second period, the subjects walked unassisted (i.e., before assisted walking). The downward-sloping curve demonstrates the characteristic aspect of festinating gait, with the gait gradually accelerating.

However, after the initiation of the auditory stimuli with the targeted phase difference of 0.2 rad (i.e., assisted walking), the subject's gait festination decreased, indicating dynamic stabilization of the walking rhythm. The observed phase difference values centered around the target phase difference, suggesting that the walking rhythms of the subject and the virtual robot were stably synchronized with a slight delay in presentation of the auditory stimuli relative to the timing of the subject's heel strike. Stride time reduction rate (decrease in stride time per second) was newly defined as the gradient, α, of the regression line for the graph of stride time versus elapsed time. When α was calculated for the subject, we noted a marked improvement (81.0%) from before assisted walking (α= -0.00213) to assisted walking (α= -0.00042). In addition, the mean phase difference for the 40 seconds of assisted walking is near the target phase difference.

TABLE II
STABILIZATION OF GAIT FESTINATION IN PARKINSON'S DISEASE

Subject No.	Stride time reduction rate ($\times 10^3$)		
	Before assisted walking	Assisted walking	After assisted walking
1	-2.13	-0.42	-1.53
2	-2.05	-0.52	-1.14

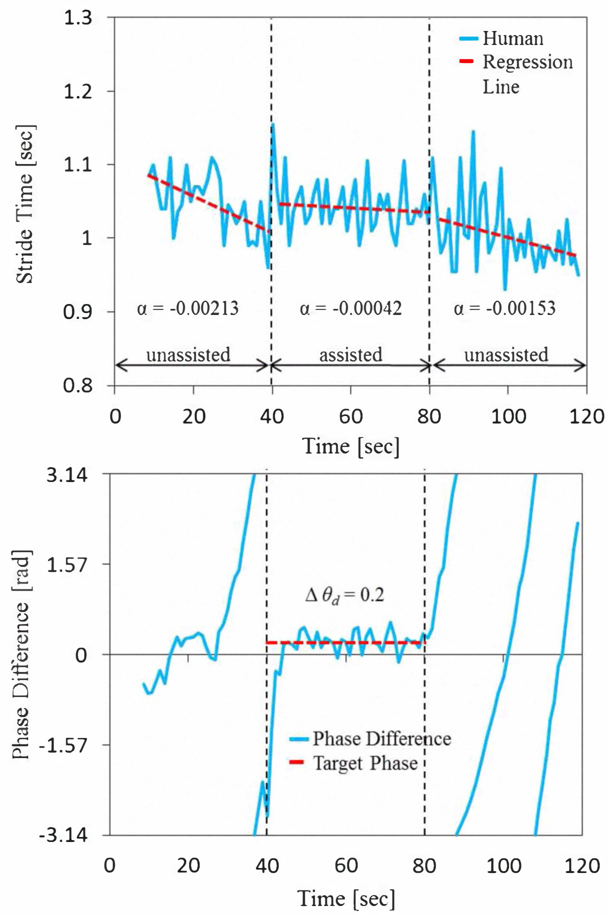

Fig. 6. Time-course changes in stride time and phase difference of the subject No. 1, achieved by the interpersonal synchrony emulation system. This result obtained in the before assisted walking, the assisted walking and the after assisted walking are compared. Every these three sections, each gradient of the regression line α was calculated. The festination gait was defined as α < -0.001.

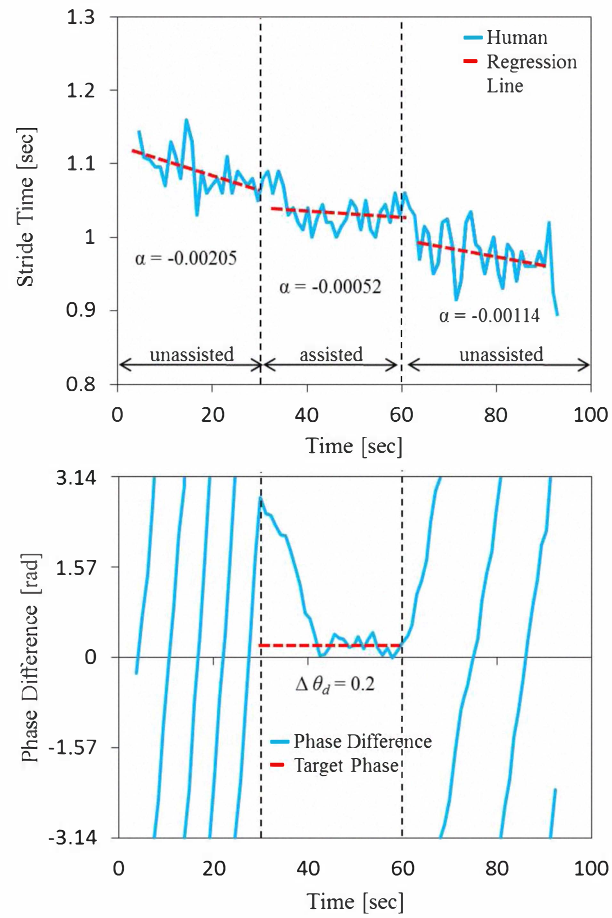

Fig. 7. Time-course changes in stride time and phase difference of the subject No. 2, achieved by the interpersonal synchrony emulation system. This result obtained in the before assisted walking, the assisted walking and the after assisted walking are compared. Every these three sections, each gradient of the regression line α was calculated. The festination gait was defined as α < -0.001.

After termination of the auditory stimuli (i.e., after assisted walking), the gait festination returned. However, the stride time reduction rate after assisted walking became closer to zero than before assisted walking. When α was calculated, we noted a marked improvement (28.2%) between the before assisted walking (α = -0.00213) and the after assisted walking (α= -0.00153).

Figure 7 provides time-course changes in stride time and phase difference in subject No.2 equipped with the system. In the first 30 second period, the subject walked with nothing and showed the gait festination because the stride time reduction rate α was under -0.001. During the subject walked with the auditory stimuli synchronizing with subject's footstep timing, the index of gait festination got nearer to zero than before. The gait festination improved 74.6% between the before assisted walking (α = -0.00205) and the assisted walking (α= 0.00052). Moreover, in this 30 seconds period, the phase difference converged in the target phase difference ($\Delta\theta_d$ = 0.2). After stopping the rhythmic sound, the subject showed little gait festination. However, the extent of the stride acceleration after assisted walking was smaller than that of before assisted walking. The gait festination improved 44.4% between the before assisted walking (α = -0.00205) and the after assisted walking (α = -0.00114). This subject No.2 also showed similar result of the subject No.1. Table II argue the results of analyzing stride time reduction rate for all subjects.

IV. Discussion

With assisted walking, the stride time reduction rate α got closer to zero compared to before assisted walking in the two subjects. During assisted walking, the phase difference converged in target phase difference ($\Delta\theta_d$ = 0.2). This phase difference indicates synchronized walking rhythm between human and virtual robot. The experimental manipulation between before assisted walking and assisted walking is the auditory stimuli provided by the interpersonal synchrony emulation system. Here, the slope of rate α near to zero means that the subjects were able to continue walking at constant speed commonly. Then, the synchronization of walking rhythm between subjects and virtual robot seemed to mitigate the symptom of gait festination.

Regarding after assisted walking, the stride time reduction rate α after assisted walking got closer to zero more than before assisted walking in the two subject. They showed the gait festination again after termination assisting with synchrony-based auditory stimuli. The stride time reduction rate was bigger than that of assisted walking. However, it was smaller than that of before assisted walking. Then, facilitation with the system seemed to have carry-over effect to improve the gait festination of PD patients.

Several researchers have previously proposed the use of constant rhythmic auditory stimuli[10],[12] and floor stripe patterns[31] in gait training for PD patients; however, these studies were one-sided stimulation and paid no attention to the mutual interaction between the rhythmic stimuli and gait cycle for realizing dynamic stability of synchronization. Our study is the first one to demonstrate the potential applicability of the interpersonal synchrony for dynamic stabilization of gait rhythm. By focusing on gait festination in PD patients, this study evaluated the effects of our system on rhythm formation disturbances resulting from the basal ganglia disease. The results showed that the interpersonal mutual entrainment and phase difference control seemed to be quite effective for dynamically stabilizing the festinating gait. In addition, the presence of carry-over effects of the gait stabilization was shown, thereby suggesting a possible application for rehabilitation and learning process in the basal ganglia[32]. Despite the small number of subjects in the present study, the process of synchronization between man and machine appears to have considerable rehabilitation potential. We suppose that these effects will strengthen and solidify in future as our sample size increases. In addition, follow-up research is warranted to clarify how this interpersonal mutual synchrony contributes to stabilization and improvement of human gait and other various rhythmic movements.

V. Conclusion

In this study, we applied an interpersonal synchrony emulation system to Parkinson's disease patients with festinating gait. We tested for improvements in gait festination and analyzed the stride time reduction rate and phase difference of subjects. Results indicated that gait stabilized and accelerated less when assisted by the system compared to unassisted walking. Moreover, carry-over effects were observed. After termination of the auditory stimuli, the gait remained stabilized. These results seem to warrant future clinical application of this interpersonal synchrony emulation system for patients with a variety of motor disorders. In the near future, we are going run more trials to test the system's effectiveness of this demonstration on the patients with Parkinson's disease.

Acknowledgment

We are deeply grateful to the people at Kanto Central Hospital whose comments, suggestions and cooperation were of inestimable value for our study.

Appendix

A. The rhythm generator model in the interpersonal synchrony emulation system

The interpersonal synchrony emulation system[22] used in this study exchanged information on the timing of footground contact between the subject and the virtual robot (Figure 1). This system had a hierarchical structure (Figure 2) consisting of two modules: Module 1 was responsible for mutual entrainment between the human stepping rhythms and the virtual robot's gait pattern, and Module 2 controlled the phase difference (shift in timing) between the sensory input (the subject's foot contact with the ground) and the motor output (production of robot footstep sound stimuli to the subject) to a targeted value.

B. Module 1 as implementing mutual entrainment of gait

Phase oscillators[18], which have been successfully used for simulating CPG's function of generating walking patterns[23],[24], were applied to express the control law for Module 1, as shown by equation (4). Here, θ_m represents the virtual robot's phase of the gait cycle, and ω_m designates the natural frequency (reciprocal of the natural period) for the walking cycle. When θ_m in equation (4) attained an integer multiple of 2π, Module 1 transmitted a tone signal to the subject, interpreting it as an indication of the virtual robot's foot making contact with the ground. The input variable of this equation, θ_h, presents the phase of the subject's gait cycle, estimated from the discontinuous timing of the subject's heel strike; K_m (> 0) designates the coupling constant.

$$\dot{\theta}_m = \omega_m + K_m \sin(\theta_h - \theta_m). \tag{4}$$

C. Module 2 as controlling the phase difference of gait

The control law for Module 2 was derived based on the following considerations. In a stable state in which two coupled rhythmic oscillators are synchronized through mutual entrainment, the relative phase advances for the oscillator with the larger natural frequency (known to occur in association with phase wave propagation)[23]. This finding enabled implementation of a feedback control for the difference in the timing of input and output of Module 1 (equivalent to $\Delta\theta_m = \theta_h - \theta_m$). The control law for Module 2 could then be presented as in equation (5), in which $\Delta\theta_m$, $\Delta\theta_d$, and μ denote the Module 1 phase difference, the target phase difference, and the control gain, respectively.

$$\dot{\omega}_m = -\mu \sin\left(\Delta\theta_d - \Delta\theta_m\right). \qquad (5)$$

The above equations can be applied for both the right and left legs, with a phase shift of π. In this study, values of 0.5 and 0.32 were used for K_m and μ, respectively.

REFERENCES

[1] J. A. Grahn and M. Brett, "Impairment of beat-based rhythm discrimination in Parkinson's disease", Cortex, Vol.45-1, pp.54-61, 2009.

[2] M. Schwartze, P. E. Keller, A. D. Patel, and S. A. Kotz, "The impact of basal ganglia lesions on sensorimotor synchronization, spontaneous motor tempo, and the detection of tempo changes", Behavioural Brain Research, Vol.216-2, pp.685-691, 2010.

[3] K. Takakusaki, K. Saitoh, H. Harada, and M. Kashiwayanagi, "Role of basal ganglia-brainstem pathways in the control of motor behaviors", Neuroscience research, Vol.50-2, pp.137-151, 2004.

[4] K. Takakusaki, "Motor control by the basal ganglia, Rinsho shinkeigaku, Vol.49-6, pp.325-333, 2009.

[5] J. S. Freeman, F. W. Cody, and W. Schady, "The influence of external timing cues upon the rhythm voluntary movements in Parkinson's disease", Journal of neurology, neurosurgery and psychiatry, Vol.56-10, pp.1078-1084, 1993.

[6] P. Brown, D. Williams, "Basal ganglia local field potential activity: Character and functional significance in the human", Clinical Neurophysiology, Vol.116-11, pp.251-259, 2005.

[7] R. Baltadijieva, N. Giladi, L. Gruendlinger, C. Peretz, and J. M. Hausdorff, "Marked alteration in the gait timing and rhythmicity of patients with de novo Parkinson's disease", European Journal of Neuroscience, Vol.24-6, pp.1815-1820, 2006.

[8] Q. J. Almeida, J. S. Frank, E. A. Roy, A. E. Patla, and M. S. Jog, "Dopaminergic Modulation of Timing Control and Variability in the Gait of Parkinson's Disease", Movement Disorders, Vol.22-12, pp.1735-1742, 2007.

[9] J. M. Hausdorff, "Gait dynamics in Parkinson's disease: Common and distinct behavior among stride length, gait variability, and fractal-like scaling", CHAOS, Vol.19-2, p.026113, 2009.

[10] M. H. Thaut, G. C. McIntosh, R. R. Rice, R. A. Miller, and J. Rathbun, and J. M. Brault, "Rhythmic Auditory Stimulation Gait Training for Parkinson's Disease Patients", Movement Disorders, Vol.11-2, pp.193-200, 1996.

[11] G. C. McIntosh, S. H. Brown, R. R. Rice, and M. H. Thaut, "Rhythmic auditory-motor facilitation of gait patterns in patients with Parkinson's disease", Journal of Neurology and Psychiatry, Vol.62-1, pp.22-26, 1997.

[12] J. M. Hausdorff, J. Lowenthal, T. Herman, L. Gruendlinger, C. Peretz, and N. Giladi, "Rhythmic auditory stimulation modulates gait variability in Parkinson's disease", European Journal of Neuroscience, Vol.26-8, pp.2369-2375, 2007.

[13] M. H. Thaut, M. Abiru, "Rhythmic Auditory Stimulation in rehabilitation of movement disorders: A Review of Current Research", Music Perception, Vol.27-4, pp.263-269, 2010.

[14] Muto T. & Miyake, Y. Analysis of the co-emergence process on humanhuman cooperative walk (in Japanese), Transaction of the Society of Instrument and Control Engineers 40, 554-562 (2004).

[15] K. Suzuki, S. Orimo, T. Nishi, Y. Miyake, "Walking stabilization of Parkinson's disease patient by support system Walk-Mate based on mutual-synchronization", Proceedings of the 25th Symposium on Biological and Physiological Engineering, pp.113-114, 2010.

[16] K. Suzuki, H. Uchitomi, M. J. Hove, T. Orimo, and Y. Miyake: The Effect of Rhythmic Auditory Stimulus on Self-similarity of Gait cycle Fluctuation in Parkinson's Disease Patients, 23th SICE Symposium on Decentralized Autonomous Systems, 1C3-2, 2011.

[17] F. A. Middleton, P. L. Strick, "Basal ganglia and cerebellar loops: motor and cognitive circuits", BRAIN RESEARCH REVIEWS, Vol.31-2-3, pp.236-250, 2000.

[18] Kuramoto, K., "Chemical Oscillations, Waves and Turbulence", Springer-Verlag, 1984.

[19] Miyake, Y. & Shimizu, H., "Mutual entrainment based human-robot communication field", Proc. of. IEEE Int. Workshop on Robot and Human Communication (Ro-Man'94), pp.118-123, 1994.

[20] Miyake, Y. et al., "Mutual-entrainment-based-communication-field in distributed autonomous robotic system: Autonomous coordinative control in unpredictable environment", In H Asama, T Fukuda, T Arai & I Endo(Eds.), Distributed Autonomous Robotic Systems, Springer-Verlag, Tokyo, pp.310-321, 1994.

[21] Miyake, Y., Miyagawa, T., & Tamura, Y., "Man-machine interaction as co-creation process", Transaction of the Society of Instrument and Control Engineers E-2, pp.195-206, 2004.

[22] Miyake, Y., "Interpersonal synchronization of body motion and the Walk-Mate walking support robot", IEEE Transactions on Robotics Vol.25, Issue.3, pp.638-644, 2009.

[23] Kopell, N. & Ermentrout, G.B., "Coupled oscillators and the design of central pattern generators", Mathematical Biosciences Vol.90, pp.87-109, 1988.

[24] Yuasa H. & Ito, M., "Coordination of many oscillators and generation of locomotory pattern", Biol. Cybern. Vol.63, pp.177-184, 1990.

[25] Orlovsky, G., Deliagina T. G. & Grillner, S., "Neural control of locomotion: From mollusk to man", Oxford University Press, 1999.

[26] Shumway-Cook A. & Woollacott, M., "Motor control: Theory and practical applications", Williams & Wilkins, 1995.

[27] Mates, J., "A model of synchronization of motor acts to a stimulus sequence: 1. Timing and error corrections", Biol. Cybern. Vol.70, pp.463-473, 1994.

[28] Miyake, Y., Onishi Y. & P¨oppel, E., "Two types of anticipation in synchronous tapping", Acta Neurobiologiae Experimentalis Vol.64, pp.415-426, 2004.

[29] Takano K. & Miyake, Y., "Two types of phase correction mechanism involved in synchronized tapping", Neuroscience Letters Vol.417, pp.196-200, 2007.

[30] Hanakawa, T., "Neuroimaging of standing and walking: Special emphasis on Parkinson gait", Parkinson and Related Disorders, Disord.12, Suppl.2, pp.S70-S75, 2006.

[31] Mestre, D., Blin O. & Serratrice, G., "Contrast sensitivity is increased in a case of nonparkinsonian freezing gait", Neurology, Vol.42, pp.189-194, 1992.

[32] Schultz, W., "Behavioral dopamine signals", Trends in Neuroscience, Vol.30, pp.259-288, 2007.