Interpersonal Synchrony-based Dynamic Stabilization of the Gait Rhythm between Human and Virtual Robot — Clinical Application to Festinating Gait of Parkinson's Disease Patient —

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Abstract:

Recently, robotics attracts attention in field of not only industry and production but also assistive technology and rehabilitation method. It is required how the system generate assistive functions in interaction with the user, while lots of one-sided help forms are in previous researches. From these backgrounds, we have focused on cooperative gait between humans as interpersonal synchronization, and modeled the mechanism of footstep rhythm synchronization. Moreover, we developed an interpersonal synchrony emulation robot named Walk-Mate, which was biped virtual robot synchronizing with the user's footstep rhythm via walking together. In this study, we evaluated the effect of Walk-Mate in stabilizing gait with Parkinson's disease (PD), which previously displayed disturbances in rhythm formation and festinating gait (accelerating footsteps). The results showed that the festinating gait, evaluated by stride time reduction rate, significantly stabilized and accelerated less with Walk-Mate compared to unassisted walking. Additionally, carry-over effects were significantly observed. After termination of the auditory stimulation, the gait remained stabilized. These suggested that gait with PD was dynamically stabilized by the interpersonal synchrony process between timing of human's gait and of external auditory cues. In this paper, we showed significant improvement for the festinating gait in the PD patients.

1. Introduction

In several nations that have increasingly elderly populations, the demands for robots and mechanical systems have expanded in order to manage the production process, complement labor force, and so on. Today, the technology of robotics is developing rapidly and is employed in many different domains. Robots that coexist with humans and helps our daily life in a cooperative manner is also being studied[1,2]. For example, humanoid-robots and robotics-suits are among the best known new technologies as they have received extensive media attention, and are representative of today's robotics[3-5].

Robotic technologies serve an important function in rehabilitation and in assistive devices. One of the most critical rehabilitative applications is in assisting human mobility, as mobility is crucial for independence and autonomy[1,2]. Several companies and research institutes have developed assistive methods based on both power-assist methods wherein an external skeleton system helps drive a human's motor function and methods related to human's cognitive function[6,7].

The robotics suit, for instance, is one of the locomotion assistive systems based on motor drive[6,7]. The system can address mobility problems, and it can also amplify a user's maximum physical power. By supplementing human movement with a motor drive, the robotics suit can provide powerful athletics function and superhuman strength in work contexts. However, it takes much time to attach the suit to a human's body and the system's calibration for the each user is not easy.

In the assistive methods related to human rehabilitation, on the other hand, sensory stimulation (as opposed to motor support) can yield successful rehabilitative function[8-12]. Visual stimulation assists a disordered gait simply by using a virtual stripe on a ground a portable head mount display provided[13-17]. Auditory stimulation can improve pathologic gait by applying fixed-tempo rhythmic auditory stimulation[11,12]. Healthy gait has fractal (1/f) dynamic structure, which degrades in certain neurological disorders; but the auditory support technology can improve impaired gait dynamics[18,19].

From these viewpoints of assistive methods, our research group has focused on the gait dynamics coexisted with cooperative walking, and modeled interpersonal synchronization between human's gait rhythms[20-25]. Based on the dynamics of cooperative gait between humans, our research group developed an interpersonal synchrony emulation robot named Walk-Mate for supporting patients with gait disturbances[24-28]. The system made interaction between patient's gait timing and an auditory rhythmic beep, and these two rhythms were synchronized. The interactive rhythm in Walk-Mate system was generated by using a nonlinear oscillator. A previous study investigated the comparison of gait improvement effects between Walk-Mate

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system and fixed-tempo rhythmic auditory stimulation, which provided the rhythmic beep with constant tempo, as one of the methods having non-interaction to patients[29]. The results indicated that the interpersonal synchrony process generated by Walk-Mate system was effective to improve gait disorders resulted from motor symptoms.

From these backgrounds, we hypothesized that an interpersonal synchrony process has potential to improve gait performances disturbed by neurodegenerative disease such as Parkinson's disease (PD). To investigate the hypothesis, we focused on the festinating gait that is one of the particular PD symptoms. The festinating gait is an alteration in gait pattern characterized by a quickening and shortening of normal strides. Because the gait speed accelerates involuntarily, the symptom shows dynamically destabilized gait, and it is also clinically important symptom of PD. We expect that the Walk-Mate as an interpersonal synchrony emulation robot has potential to mitigate the festinating gait through dynamically stabilizing gait. Therefore, the purpose of this study is to investigate the effectiveness on improving the PD patients' festinating gait to apply the function generated by Walk-Mate to dynamically stabilize gait.

2. MATERIALS

2.1 Walk-Mate System

An overview of our experimental system is shown in Figure 1. Figure 1 (a) illustrates Walk-Mate system, included

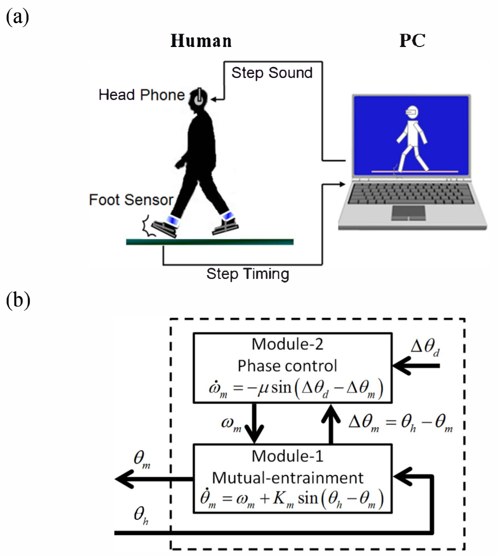

Fig.1 An overview of an experimental system. (a) Depiction of an interpersonal synchrony emulation robot named Walk-Mate. (b) Walk-Mate's timing system used nonlinear oscillators and was organized hierarchically in two modules. Module 1 mutually entrained the gait frequencies of the computer and the participant. Module 2 adjusted the relative phase difference between the computer's auditory onset and the participant's step contact to a target phase difference.

a cross-feedback process, whereby the footstep timing of biped virtual robot was given as an input signal to the subject, while the robot was provided with the subject's footstep timing. The rhythm generator model in the biped virtual robot had a hierarchical structure, as illustrated in Figure 1 (b). Module 1 was responsible for mutual entrainment between the human footstep timing and the virtual robot's footstep timing. Module 2 controlled the phase difference (shift in timing) between the sensory input, which is the subject's footstep timing, and the motor output, which is production of robot footstep sound stimuli to the subject, to a targeted value. More specifically, Module 1 involved the use of a non-linear phase oscillator[30], which has been shown to be effective for simulating CPGs[31]. Module 2 implemented feedback control for the phase difference in the timings of input and output of Module 1.

The relevance of the rhythm generator 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[32-34]. It was further supported by the dual process model[35] and our experimental results in synchronization tapping[36,37].

2.2 Function of Walk-Mate System

Figure 2 shows an instance of time-course changes in the stride interval time and phase difference achieved by Walk-Mate system. 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 of the subject and the virtual robot were synchronized with the targeted phase shift of 0.2 rad. This meant a slight delay in presentation of the auditory stimuli relative to the time point of the subject's footstep timing.

Firstly, during the walk without any assistance (0-60 sec), the subject and the virtual robot independently walked at different stride interval time. Secondly, during the walk assisted by Walk-Mate system (60-120 sec), their stride interval time drew closer to each other via mutual entrainment. Simultaneously the phase difference between the subject and the virtual robot stably converged to the target value set to 0 rad. Finally, during the condition when the target phase difference was set to 0.2 rad (120-180 sec), the subjects' gait slowed down. Their stride interval times increased automatically without being aware of the phase difference.

This phenomenon has potential being useful to stabilize festinating gait of PD. These results showed that the stride interval time could be manipulated by controlling the target phase difference in mutual synchronization between the subject and the virtual robot.

3. METHODS

3.1 Experimental Subjects

Twenty one PD patients participated in an experimental task of this study. They are normal-hearing and non-demented patients. There were eight men and thirteen women. The subjects' average age was 75.3±7.62 years (Mean±S.D.). The average disease duration was 5.71±3.65 years. The average of modified Hoehn and Yahr stage (modified HY) was 2.83±0.29. Part 2 of Unified Parkinson's Disease Rating Scale (UPDRS) was 9.76±4.52 and part 3 of UPDRS was 22.4±6.77. Here, Modified HY and UPDRS (part 2 and part 3) are the representative severity indicators of PD.

The subjects exhibited festinating gait during a prescreening interview with the physician, and were receiving dopaminergic medications for treatment of PD. Their modified HY (range: 0-5) were 2 or 3, indicating independent ambulation. All subjects provided written informed consent before participation.

3.2 Experimental Task

PD subjects were instructed to walk along the path in the corridor. At predefined intervals, they were exposed to rhythmic cues presented by Walk-Mate 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 80m. The subjects were instructed to make a pretest walk for 80m to familiarize with the system and environment, without presentation of rhythmic sound stimuli, meaning non-assistance. Then, after a 5 minutes rest, they were given the following task. One round of the 80m walking task included a sequence of unassisted walk, synchronized walk with presentation of step-guiding cues, and unassisted walk again. This study was approved by the Kanto Central Hospital Ethics Committee.

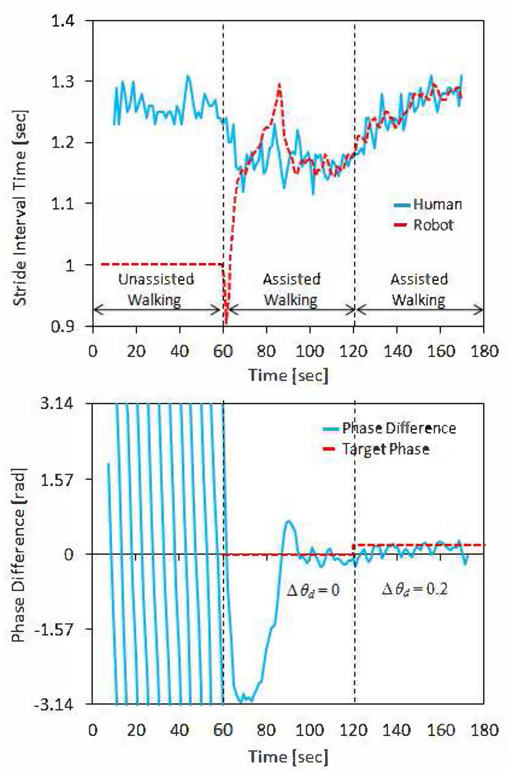

Fig.2 Examples of time-course changes in the stride time and phase difference of a healthy subject, achieved by Walk-Mate.

3.3 Experimental Setup

In specific terms, the timing of the footstep timing of biped virtual robot was presented to the subject as an auditory stimulus (combination of F5 and C5 notes, 10ms duration) via headphone (HP-RX500, Victor, Japan). The footstep timing of the subject was detected by a pressure sensors (OT-21BPG, Ojiden, Japan) fixed underneath the shoes. 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 footstep timing were performed in real time at 10ms intervals. The Walk-Mate system was intended to achieve interpersonal gait synchrony between the subject and the virtual robot.

3.4 Gait Parameters

In order to evaluate the festinating gait of the subjects, we utilized the time series data of human's stride interval time. The human stride interval time, T_h, is shown in equation (1), in which T_h is defined as the difference between the footstep 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).

$$T_h(i) = t_h(i+1) - t_h(i) \tag{1}$$

Here, the human's phase difference $\Delta\theta_h(i)$ for the i-th step is determined based on the difference between $t_h(i)$ (i.e., the time at which the subject makes i-th footstep) and $t_m(i)$ (i.e., the time at which the auditory stimulus is presented in response to the i-th footstep), 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 footstep.

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

3.5 Quantification of Festinating Gait

Festinating gait refers to a clinical manifestation in which both the stride interval times and the stride length decrease over time during walking. In this study, we paid attention to the decrease of stride interval time and conducted least-squares linear regression analysis to estimate the temporal change in stride interval time. Regarding the analysis, 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 interval time per second. In this analysis, based on preliminary analysis results (Mean±S.D. of α: $0.05\times10^{-3}\pm 0.12\times10^{-3}$) obtained from 10 healthy subjects (9 males and 1 females, mean age: 24.3 years) under the same experimental conditions, we defined festinating gait as $\alpha < -0.001$.

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

4. RESULTS AND DISCUSSION

A representative results of the time-course changes in stride interval time and phase difference in a PD subject equipped with Walk-Mate system was illustrated in figure 3.

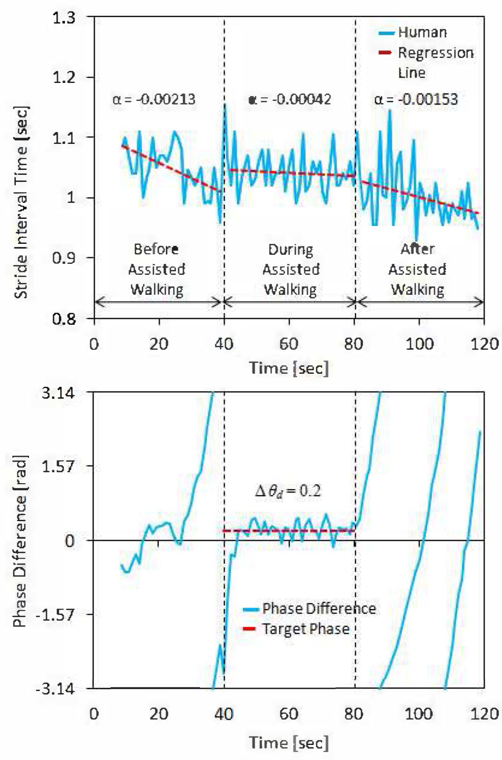

Fig.3 Examples of a result of the time-course changes in stride time and phase difference of a subject, achieved by Walk-Mate system. This result obtained in the before assisted walking, the assisted walking and the after assisted walking are compared. Every these three sections, each gradient of the regression line α was calculated. The festinating gait was defined as α < -0.001.

In the first 40 second period, the subject walked alone without any assistance (i.e., before-assisted walking). The downward-sloping curve demonstrates the characteristic aspect of festinating gait in time series of stride interval time, with the gait gradually accelerating.

However, during walking with the auditory cues with the targeted phase difference of 0.2 rad (i.e., during-assisted walking), the degree of subject's festinating gait decreased. It indicated dynamic stabilization of the gait rhythm. The phase difference values observed in the figure converged around the target phase difference of 0.2. It suggested that the gait rhythms of the subject and the virtual robot were stably synchronized with a slight delay in presentation of the auditory cues relative to the timing of the subject's footstep. Stride time reduction rate (decrease in stride interval 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 ($\alpha = -2.13\times10^{-3}$) to during-assisted walking ($\alpha = -0.42\times10^{-3}$). In addition, the mean of the phase difference for the 40 seconds of during-assisted walking is near the target phase difference.

After end of the auditory cues (i.e., after-assisted walking), the festinating gait returned. However, the value of stride time reduction rate, α, after assisted walking became closer to zero than that before assisted walking. When α was calculated, we noted a marked improvement (28.2%) between the before-assisted walking ($\alpha = -2.13\times10^{-3}$) and the after-assisted walking ($\alpha = -1.53\times10^{-3}$).

The results for all twenty-one subjects of the statistical analysis are summarized in Figure 4. Based on preliminary analysis results (Mean±S.D. of α: $0.05\times10^{-3}\pm0.12\times10^{-3}$) obtained from 10 normal healthy subjects (9 males and 1 females, mean age: 24.3 years) under the same experimental conditions, we defined festinating gait as $\alpha < -1.00\times10^{-3}$. Nineteen of the 21 subjects showed a festinating gait, and were chosen as the study cohort, because this subgroup demonstrated a significant difference in α relative to the normal subjects that participated in this study [two-tailed t-test, $p < 0.001$, $t(27) = 7.49$].

The experimental cohort demonstrated less festinating gait in the during-assisted walking (Mean $\alpha = -0.68\times10^{-3}$) compared to the before-assisted walking (Mean $\alpha = -2.78\times10^{-3}$), as indicated by a significant difference in α [two-tailed paired t-test, $p < 0.001$, $t(18) = 5.65$]. Sixteen subjects of this study cohort ($N = 19$) showed an improvement. Moreover, the α value for the during-assisted walk of these PD patients was not significantly different from that of the normal healthy group of subjects (mean $\alpha = 0.05\times10^{-3}$) [two-tailed t-test, $p > 0.05$, $t(27) = 1.77$]. As shown in Figure 4, these results indicate a remarkable alleviation of festinating gait for the study cohort ($N = 19$) during the assisted walk period, with the mean improvement of 75.3% for the stride time reduction rate. This

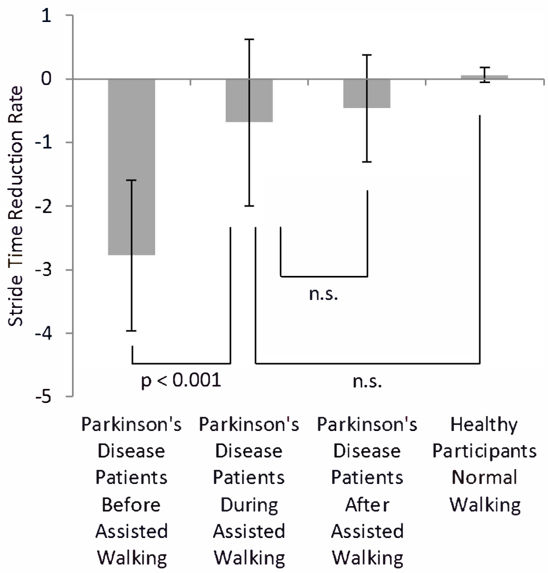

Fig.4 Statistical analysis results of stride time reduction rate. Results obtained in the before-assisted walking, the during-assisted walking by Walk-Mate system, and the after-assisted walking in Parkinson's disease patients, and healthy participants normal walking are compared. Gradient values for the regression lines represented time-dependent reduction in stride interval time. Error bars indicate standard deviations.

improvement provides clear evidence for the effectiveness of Walk-Mate system in improving the stability of festinating gait in PD patients.

Furthermore, the stride time reduction rate, α, value was calculated in the period following end of the auditory stimuli in the PD patients in which the duration of the after-assisted walking was more than 20 sec. As shown in Table 1, the α value of the after-assisted walking was obtained from 10 subjects of the study cohort (N = 19). The results show that the mean α value of the after-assisted walk (Mean $\alpha = -0.46\times10^{-3}$) was not significantly different from that of the during-assisted walking (mean $\alpha = -0.68\times10^{-3}$) [two-tailed t-test, $p > 0.05$, $t(27) = 0.48$]. These results indicate a remarkable carry-over effect of stabilization in the after-assisted walking period as shown in Figure 4, with the mean improvement of 83.5% for the stride time reduction rate. In particular, the α value of the after-assisted walk was much larger than that of the during-assisted walk. Such an over-enhanced carry-over effects of diminished stride time reduction rate was observed in 6 subjects of the above 10 subjects.

Previous research has proposed the use of fixed-tempo rhythmic auditory stimulation and floor stripe patterns in gait training for PD patients. However, these studies paid no attention to the dynamic stability of the earlier synchronization between the rhythmic stimulation and the gait rhythm. Our investigation is a prime demonstration of the potential applicability of the interpersonal synchrony process for dynamic stabilization of gait performance.

By focusing on festinating gait in PD patients, this study evaluated the influences of Walk-Mate system on rhythm formation disturbances resulting from the neurodegenerative diseases in basal ganglia. The results suggested that the interpersonal synchrony process was quite effective for dynamically stabilizing the festinating gait. In addition, the results indicated that the presence of carry-over effects of the gait stabilization, thereby suggesting a possible application for reinforcing the time series processing in the basal ganglia[38]. The evidence enhanced the previous study[39,40], which showed interpersonal synchrony process restored stride interval time fluctuation dynamically compared to gait of healthy persons, and indicated the system was effectiveness for improving clinically important gait disturbances. Follow-up research is warranted to clarify how Walk-Mate as the interpersonal synchrony emulation robot contributes to stabilization and improvement of human gait and other various rhythmic movements.

5. Conclusion

This present investigation applied Walk-Mate system to PD patients having symptom of the festinating gait. We examined the improvements in festinating gait, and analyzed the stride time reduction rate and phase difference of the subjects. Results indicated that festinating gait significantly stabilized and accelerated less when assisted by the system compared to unassisted walking. Additionally, carry-over effects were significantly observed. After end of the rhythmic cues generated by the system as assistance, the gait remained stabilized. Festinating gait often causes falling in PD patients. The application of this kind system has a potential to keep from falling in the daily life. Further works for the prevention of falling and carry-over effect will be planned. The results warrant future clinical application of Walk-Mate system for patients with a variety of movement disorders associated with neurodegenerative diseases.

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