Interpersonal Synchronization of Body Motion and the Walk-Mate Walking Support Robot

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***Abstract*—Everyone has probably experienced the phenomenon where their footsteps unconsciously synchronize with their partner while walking together. This interpersonal synchronization of body motion has been widely observed and is significant in the context of social psychology. However, the mechanism of this embodied cooperation still remains obscure and has not been substantially developed as an engineering application. In this study, by assuming "mutual entrainment" as an interpersonal synchronization mechanism, we establish a new cooperative walking system between a walking human and a walking robot (an agent as a virtual robot). In this system, rhythmic sounds corresponding to the timing of footsteps are exchanged between them on the basis of our previous studies. As a result, it was demonstrated that the two walking rhythms adapt mutually after the start of interaction, and stable synchronization is generated automatically. This global entrained state exhibits dynamic stability with small fluctuation in the walking period. Applying this method to walking support for Parkinson's disease and hemiplegia patients, its effectiveness in stabilizing the walking of the patient was shown. These results indicate the importance of interpersonal mutual entrainment of rhythmic motion for walking support, and new human–robot interaction technologies are expected as an extension of this framework.**

***Index Terms*—Human–robot interaction, mutual entrainment, walking support, Walk-Mate.**

I. Introduction

Everyone has probably experienced the phenomenon where their footsteps unconsciously synchronize with their partner while walking together. This interpersonal synchronization of body motion has been widely observed and is significant in the context of social psychology [1]–[3] and developmental psychology [4]–[6]. However, the mechanism for this type of embodied cooperation still remains obscure and has not been substantially developed as an engineering application. This study therefore hypothesizes "mutual entrainment" [7]–[9] as a synchronization mechanism, and we establish a new cooperative walking system between a walking human and a walking robot (an agent as a virtual robot; Walk-Mate).

Automatic interpersonal synchronization of body motion is widely observed in social communication and collaboration. Condon and Sander, for example, analyzed the onset timing of an infant's body motion with his mother's utterances and reported an interpersonal synchronization between them [2]. Matarazzo *et al.* analyzed the conversational process between an interviewer and an interviewee and clarified a similar phenomenon in which the utterance duration, utterance speed, and switching pause are tuned among speakers [1]. Our group has already reported a similar synchronization phenomenon between walking rhythms during interpersonal cooperative walking [10].

This type of automatic synchronization can be considered to be an effect of dynamic interaction between nonlinear oscillators. In the cooperative walking mechanism, the interaction between neural rhythms generated by a central pattern generator (CPG) [11] is considered to be

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a key mechanism of this phenomenon. Their intersegment and interlimb coordination has also been analyzed as a synchronization phenomenon [12]–[14]. Yuasa and Ito, for example, have reported an interlimb synchronization model using nonlinear dynamics, such as "entrainment" [15]. Taga also proposed a similar "global entrainment" mechanism between a neural rhythm generator and body motion to explain bipedal locomotion [16], [17]. However, these researches still remain at the stage of intrapersonal control, and the problem of cooperative walking involving interpersonal synchronization has yet to be clarified.

In terms of an engineering application, on the other hand, this synchronization phenomenon is thought to be applicable to walking support for gait disturbance. Cooperative behavior between therapist and client has already been reported in this area [18]. Similar synchronized walking is widely observed in gait rehabilitation training, which further suggests its effectiveness [19]. However, walking support robots, such as RoboKnee, are passive systems, which are operated by physiological information obtained from human motion [20]. Recently, walking support systems, such as HAL-3, that use electromyography (EMG) have also been proposed to construct power assist robots for walking [21]. These approaches still remain at the stage of master–slave control in human–robot interaction, and no mutual interaction dynamics, such as synchronization in cooperative walking, has yet to be considered.

From this background, in this study, we aim to investigate interpersonal synchronization in cooperative walking and hypothesize "mutual-entrainment" dynamics as a mechanism. We also implement this concept as an engineering application by way of a new human–robot interaction system that provides walking support for gait disturbance on the basis of our previous studies [22]–[25].

In the next section, we show how this is implemented as a system in which rhythm sounds corresponding to the timing of footsteps are exchanged between a human and a virtual walking robot. In Section III, we show that these two walking rhythms mutually adapt to each other, and its effectiveness for walking support is tested on Parkinson's disease and hemiplegia patients. Finally, the importance of interpersonal synchronization of rhythmic motion in walking rehabilitation and possibilities for a new human–robot interaction technology are discussed.

II. Methods

A. Fundamental Framework

The fundamental framework of the cooperative walking robot is shown in Fig. 1(a). The timing of a footstep on the human side is transmitted to the robot side as the timing of sensory input and, similarly, the timing of a footstep (motor output) on the robot side is transmitted to the human side as the timing of sound stimulus. As illustrated in Fig. 1(b), the control model for interpersonal cooperative walking is a hierarchical nonlinear oscillator system comprising a module for attaining mutual entrainment between an artificial rhythm generator and human walking rhythm (module 1) and a module for adjusting the timing difference (phase difference) between the sensory input θ_h and the motor output θ_m (module 2). This arrangement is utilized because control of human walking is hierarchized into a synchronization mechanism dependent on the CPG and a feedback mechanism through the cerebellum and brainstem [26], [27]. Module 1, in particular, was constructed by using a nonlinear phase oscillator [7]–[9], and module 2 controls the phase difference $\Delta\theta_m (= \theta_m - \theta_h)$ to converge on a target phase difference $\Delta\theta_d$. Our previous studies on timing control of human motion also support such modeling [28], [29].

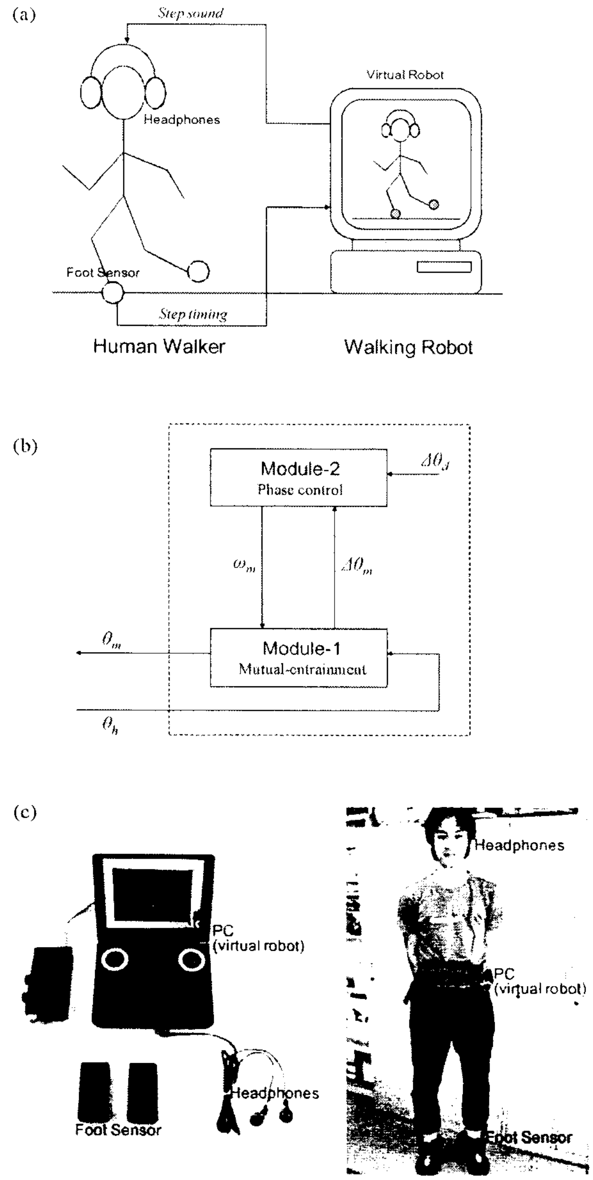

Fig. 1. Cooperative walking system. (a) Cooperative walking system utilizes a cross-feedback system to share the walking rhythm between a human and a walking robot. (b) Cooperative walking control model has a module attaining mutual entrainment between walking rhythms and a module for controlling the timing difference between sensory input and motor output. (c) Experimental system consists of a PC that simulates the virtual walking robot, foot (acceleration) sensors for detecting footsteps, and headphones for providing sound stimuli. The foot sensors are attached to both ankles, and the PC can be placed in a waist pouch.

B. Walk-Mate System

Fig. 1(c) shows an example of how the system is actually implemented. In this experimental system, the cooperative walking is performed by a walking agent serving as a virtual biped robot and a human subject. The footstep timing of the walking robot is presented as sound stimuli (duration 100 ms) to the human through headphones, and the footstep timing of the human is detected by acceleration sensors (ADXL202E, Analog Devices) and transmitted to the walking robot that is simulated by a portable PC (PCG-U101, SONY). The footstep measurement, simulation of the virtual walking robot, and storage of the experimental data were performed every 10 ms. These tasks were controlled using a multimedia timer on Windows XP (Microsoft). This experimental system is called "Walk-Mate."

C. Control Model of Cooperative Walking

The hierarchical control model for cooperative walking has two modules. Module 1 consists of a phase oscillator [7], [8], which is considered an appropriate model for a CPG [12]–[14]. This generates a walking rhythm as

$$\dot{\theta}_m = \omega_m - K_m \sin(\Delta\theta_m) \tag{1}$$

where θ_m is the phase of the robot walking rhythm, and ω_m is the natural frequency of the walking rhythm. The timing at which θ_m becomes a multiple of 2π is defined as the footstep timing, and the sound stimuli are provided discretely to the human at this timing. Here, $\Delta\theta_m$ is the phase difference between the sensory input θ_h and the motor output θ_m. Since θ_h is the phase of human walking rhythm estimated from the discrete timing of the human footsteps, the phase difference $\Delta\theta_m$ is discretely updated (see Section II-D for details). Here, K_m (>0) is the coupling constant, and the coupling function is assumed to be symmetrical for purposes of simplicity. Mutual entrainment between the human and robot is therefore obtained when the following condition is satisfied:

$$\left|\frac{(\omega_m - \omega_h)}{(K_m + K_h)}\right| \leq 1 \tag{2}$$

where ω_h and K_h are, respectively, the natural frequency and the coupling constant for the human subject.

The timing control between sensory input and motor output in the module 2 is as follows. It is known that in a steady state in which two rhythms are synchronized by mutual entrainment, the rhythm having the higher natural frequency is relatively advanced in phase [12], [13]. This is called the travelling wave. Feedback control of the timing difference between input and output in the module 1 is therefore implemented by utilizing this dynamic relation. By defining the phase difference in the module 1 as $\Delta\theta_m (=\theta_m - \theta_h)$, a method to control the natural frequency ω_m that attains the target phase difference can be expressed as

$$\dot{\omega}_m = -\mu \sin(\Delta\theta_m - \Delta\theta_d) \tag{3}$$

where $\Delta\theta_d$ is the target phase difference, and μ (> 0) is the control gain. Here, the phase difference $\Delta\theta_m$ is discretely updated, and therefore, ω_m is also updated discretely.

The set of equations is applied to both the right and left legs. In the case of a nondisabled subject, the right and left legs move at a phase difference of π. In this study, $K_m = 0.5$, and $\mu = 0.32$ are used.

D. Definition of Period and Phase Difference

Sensory input corresponding to the phase of the human walking rhythm θ_h cannot be measured continuously because the input signal from the human subject is only the footstep timing. This phase difference is therefore discretely calculated based on the time difference between the sensory input corresponding to the human footsteps and the motor output corresponding to the robot footsteps. The walking period is also defined as the time difference between two successive footsteps by the same leg, and these discretely estimated values are used in the aforementioned model.

The walking period on the robot side T_m is defined by (4), shown below. The difference between the time $t_{m,i+1}$ of the footstep in the $(i+1)$th step and the time $t_{m,i}$ of the footstep in the ith step with the same leg is defined as the walking period $T_m(t_{m,i})$ in the ith step as follows:

$$T_m(t_{m,i}) = t_{m,i+1} - t_{m,i}. \tag{4}$$

A similar definition is also used to calculate the human walking period T_h.

The phase difference $\Delta\theta_m(t_{m,i})$ in the ith step at the robot is defined based on the difference between the time $t_{h,i}$ of human footsteps corresponding to sensory input to the robot and the time $t_{m,i}$ of robot footsteps corresponding to motor output to the human subject. This can be regarded as the approximate phase difference $\Delta\theta_m$ of the control model at the footstep timing, which is described as

$$\Delta\theta_m(t_{m,i}) = -(t_{m,i} - t_{h,i})\frac{2\pi}{T_m(t_{m,i})}. \tag{5}$$

E. Task and Subjects

The subjects were put on the cooperative walking system Walk-Mate and instructed to walk in time with the specified rhythm but without concentrating on the sound stimuli itself. They walked for a fixed time interval in a corridor, which was flat and straight and was about 60 m long (for nondisabled persons) or about 30 m long (for patients). The room temperature, lighting intensity, etc., were adjusted to comfortable levels, and the measurement was made under the condition that there were no other walkers except the subject.

To estimate effectiveness as walking support, a pseudogait disturbance was applied to nondisabled subjects in the first stage and was then applied to actual patients. In pseudogait disturbance, the subject's left knee was clamped with tape (Kinesio Tex Tape, KINESIO) and a load (12 kg) was attached to the ankle (Ankle Weight H8540, TOEI LIGHT) of the same leg. Six male students in their twenties (mean age 25.6 years) volunteered to serve as the nondisabled subjects.

Patients without any hearing disorder and who could walk without a stick or a walker served as subjects with gait disturbances. These subjects were six patients with hemiplegia due to brain infraction (H1: 43-year-old male, H2: 47-year-old male, H3: 71-year-old male, H4: 72-year-old female, H5: 83-year-old female, H6: 86-year-old male, Brunnstrom's stage [30] IV to V) and two Parkinson's disease patients (P1: 72-year-old male, P2: 87-year-old female with drug-induced parkisonism). This experiment involving patients was approved by the ethics committees from Takamori-so Daycare Center (Atsugi, Kanagawa, Japan) and Nissan Tamagawa Hospital (Setagaya, Tokyo, Japan).

III. Results and Discussions

A. Dynamics of Cooperative Walking

Fig. 2 shows an example of the temporal development of walking periods. At first, the human subjects and the robot walked at different periods (mean period between 30 and 60 s, $T_h = 1.24$ s, $T_m = 1.00$ s). After the cooperative walking started, these gradually became closer to each other and were then synchronized at a period approximately at a midpoint between them until the end of this interaction (mean period between 90 and 120 s, $T_h = T_m = 1.16$ s), with no significant difference observed (two-tailed t-test, $t(50) = 0.85$, $P = 0.40$). The target phase difference $\Delta\theta_d$ in this cooperative walking was 0 rad. This synchronization was observed in all subjects ($N = 6$), and a similar phenomenon has already been reported in cooperative walking between two humans [10]. Mutual-entrainment dynamics was in this way shown to be a key mechanism for interpersonal synchronization of the walking.

An interesting phenomenon in terms of walking support was also found in the amplitude of the fluctuation in the walking period through this mutual entrainment. As shown in Fig. 2, the fluctuation in the period for human subjects during cooperative walking (mean fluctuation of period between 90 and 120 s, $F_h = 0.024$ s) decreased significantly (two-tailed t-test, $t(51) = 2.12$, $P < 0.05$) as compared with that before the start of cooperative walking (mean fluctuation in period between

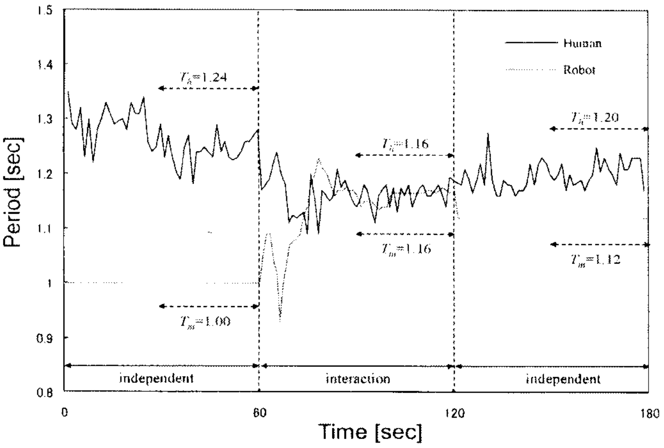

Fig. 2. Interpersonal mutual entrainment of walking rhythms. An example of temporal development of walking period. The left broken line indicates the start of cooperative walking, and the right broken line indicates the end of it.

30 and 60 s, $F_h = 0.040$ s), and this phenomenon was also observed in all the subjects ($N = 6$). Here, fluctuation was estimated by (6). This result strongly suggests the effectiveness of mutual entrainment in dynamically stabilizing the walking process. A movie of this phenomenon can be seen on our Web site.[1]

In a spectral analysis of these fluctuations in the period, a $1/f^{\alpha}$-type power spectrum was observed during independent walking by nondisabled persons [see Fig. 3(a)] as in previous studies [31] but disappeared in the subjects with a pseudogait disturbance [see Fig. 3(b)]. However, a similar $1/f^{\alpha}$ -type power spectrum was restored in the case of cooperative walking with the Walk-Mate system [see Fig. 3(c)]. Particularly, in the average of gradients α among the subjects ($N = 6$) obtained from regression lines, no significant difference was found between cooperative walking (mean gradient, $\alpha_h = 0.50$) and independent walking of nondisabled persons (mean gradient $\alpha_h = 0.66$) (two-tailed t-test, $t(10) = 1.44$, $P = 0.18$). However, the $1/f^{\alpha}$ -type power spectrum was not restored when they walked in synchronism with sound stimuli having a fixed rhythm [see Fig. 3(d)] (walking with fixed rhythm: mean gradient $\alpha_h = 0.08$, cooperative walking: mean gradient $\alpha_h = 0.50$, two-tailed t-test, $t(10) = 7.47$, $P < 0.01$). Rehabilitation in which the patients walk in synchronism with fixed rhythmic sounds (such as a metronome) or a regular stripe pattern on the floor has been proposed [32], [33]. The results here indicate that cooperative walking through mutual entrainment is essential for recovery to a stable and natural walking state. All subjects ($N = 6$) also stated that they feel greater stability and more of a sense of togetherness in cooperative walking with Walk-Mate than when walking at a fixed rhythm.

Furthermore, the mechanism of mutual entrainment was revealed. Fig. 4(a) shows examples of temporal development among phase differences $\Delta\theta_m$ and walking periods of human subjects T_h when the target phase difference $\Delta\theta_d$ was changed to ±0.5 rad from 0 rad. This indicates that stable synchronized walking occurred between the human subjects and the robot and that the phase difference $\Delta\theta_m$ converged to the target value. Under this condition, the human walking period decreased when the motor output timing preceded the sensory input timing ($\Delta\theta_m > 0$) and increased in the opposite case. This means that

[1]Movie of independent walking of gait disturbance is available at http://www.myk.dis.titech.ac.jp/2007hp/theme/DVwalk-mate1.mpg and cooperative walking with Walk-Mate is shown at http://www.myk.dis.titech.ac.jp/2007hp/theme/DVwalk-mate2.mpg

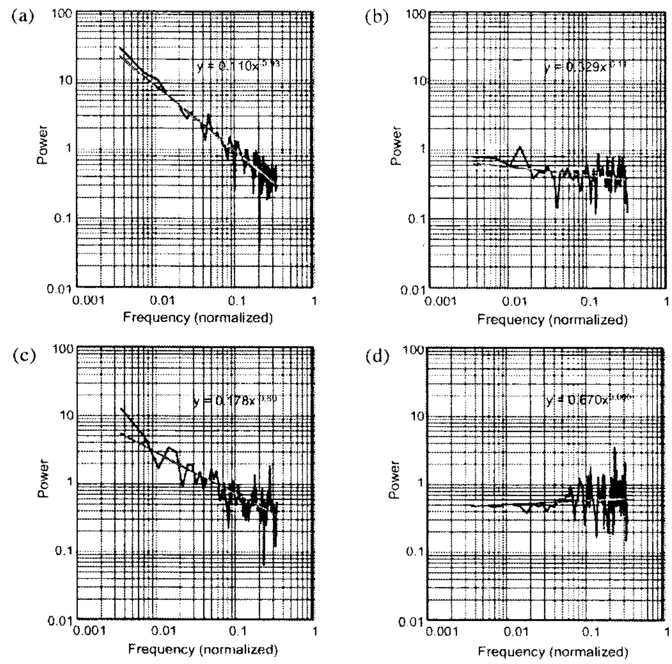

Fig. 3. Power spectra of fluctuations in walking period. The power spectrum was obtained by applying a discrete Fourier transform (DFT) to the time series of walking period data for 256 steps. The frequency is a relative value obtained using the length of time for one step as the interval size. Regression lines were added in double logarithmic plots. Each graph is for (a) independent walking by nondisabled subjects, (b) independent walking with pseudogait disturbance, (c) cooperative walking with pseudogait disturbance, and (d) fixed-rhythm walking with pseudogait disturbance.

the human walking period decreases when the robot footstep timing precedes the human footstep timing and *vice versa*. The relationship between the target phase difference and the change in the human walking period is further estimated in Fig. 4(b). This result also supports the aforementioned interpretation. In other words, a sensory-motor coupling to realize the mutual entrainment by which the walking period is controlled such that the phase difference decreases was indicated on the human side. This demonstrates the validity of our cooperative walking model based on mutual-entrainment dynamics.

B. Application to Gait Disturbance

We next explored the possibilities of this interpersonal mutual-entrainment mechanism as walking support for actual patients. We first of all focused on the festinating gait, which is one abnormal postural reflex caused by Parkinson's disease. The festinating gait is a symptom where the walking period gradually becomes shorter, and the patient eventually falls down [32], [33].

Fig. 5(a) shows an example of temporal development of the walking period of an 87-year-old female patient (P2). In the first 1 min, the characteristics of festinating gait were obvious, and the walking period gradually became shorter. However, after starting cooperative walking with Walk-Mate, the decrease in the walking period slowed, and her walking stabilized. When the gradients γ of regression lines obtained from rates of change in the walking period were compared as an index of acceleration, a significant difference was observed between independent walking (gradient between 20 and 60 s, $\gamma_h = -0.0052$) and cooperative walking (gradient between 120 and 160 s, $\gamma_h = -0.0001$). This tendency was observed in two out of two patients. Here, mutual entrainment with a negative target phase difference (-0.25 rad)

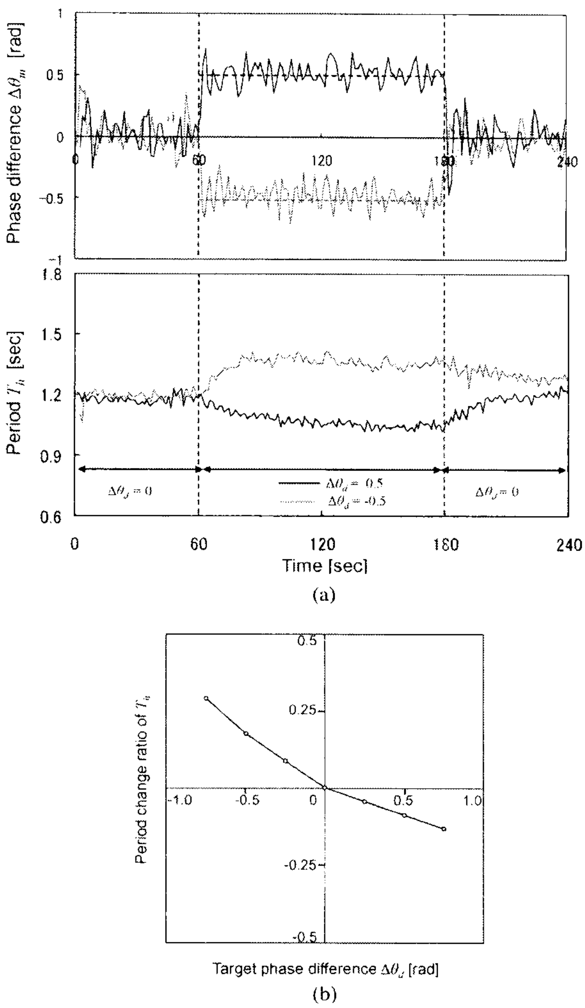

Fig. 4. Timing control of mutual entrainment. (a) Examples of temporal development of phase difference on the robot (upper) and walking period on the human (lower) when the target phase difference $\Delta\theta_d$ was controlled. The left broken line indicates the change in target phase difference from 0 rad to a designated value (±0.5 rad), and the right line indicates the restoration to 0 rad. (b) Relationship between target phase difference and the change in the walking period of the human subject is shown. This period change was obtained by subtracting the average between 120 and 180 s from the average between 0 and 60 s.

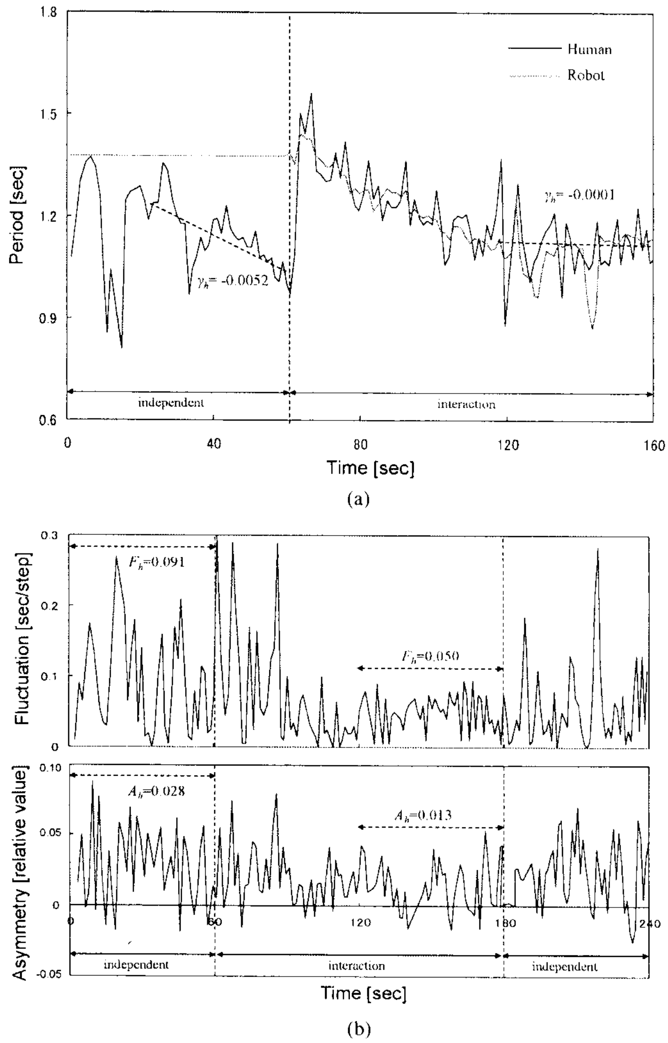

Fig. 5. Application to gait disturbance. (a) Example of temporal development of walking period in festinating gait of Parkinson's disease. The broken line indicates the start of cooperative walking. (b) Example of temporal development of walking period fluctuation (upper) and left–right asymmetry of walking (lower) in unstable gait of hemiplegia. The left broken line indicates the start of cooperative walking, and the right line indicates its end.

representing the delay in robot footstep timing relative to the human footstep timing was utilized. This timing is thought useful for decelerating the festinating gate. These results suggest that interpersonal mutual entrainment is effective in stabilizing the festinating gait of patients with Parkinson's disease.

We next focused attention on the unstable gait of hemiplegia patients. In hemiplegia, there is a delay in the footstep timing of the affected leg compared with the unaffected leg [34]. Fig. 5(b) shows temporal development of the fluctuation in walking period and left–right asymmetry in the walking pattern of an 86-year-old male patient (H6).

The fluctuation in walking period $F_h(t_{h,i})$ in the ith step of the human subjects was evaluated as an absolute value of the variation in walking period within p steps (in this study, we used $p = 3$), which is shown as

$$F_h(t_{h,i}) = |T_h(t_{h,i+p}) - T_h(t_{h,i})|. \tag{6}$$

We use the averaged value of this fluctuation within a fixed time interval as an index of the stability of walking motion. The smaller value corresponds to the smaller fluctuation (stable walking).

The left–right asymmetry of walking $A_h(t_{h,i})$ in the ith step by the human subject is defined as a value obtained by normalizing the difference between the time length from the right footstep to the left footstep and the time length from the left footstep to the right footstep in successive steps in the walking period at that time, which is shown as

$$A_h(t_{h,r,i}) = \frac{(t_{h,r,i+1} - t_{h,l,i}) - (t_{h,l,i} - t_{h,r,i})}{T_h(t_{h,r,i})} \tag{7}$$

where $t_{h,r,i}$ and $t_{h,l,i}$ are the respective times of the footstep in the ith step of right and left legs. We use an averaged value of this asymmetry within a fixed time interval as an index of the left–right symmetry of the walking motion. The 0 value denotes symmetry, and the larger absolute value results in greater asymmetry.

After cooperative walking started, the fluctuation in the period observed during independent walking (mean fluctuation between 0 and 60 s, $F_h = 0.091$ s) decreased to a small fluctuation (mean fluctuation between 120 and 180 s, $F_h = 0.050$ s), suggesting significant stabilization (two-tailed t-test, $t(88) = 3.63$, $P < 0.01$) (see Fig. 5(b), upper). The left–right asymmetry observed in independent walking (mean asymmetry between 0 and 60 s, $A_h = 0.028$) was also significantly reduced during cooperative walking (mean asymmetry between 120 and 180 s: $A_h = 0.013$, two-tailed t-test, $t(84) = 2.87$, $P < 0.01$) (see Fig. 5(b), lower). This was effective in reducing the fluctuation period in five patients out of six. The remaining one patient (H4) also suffered from gait disturbance due to a bone fracture and was the most critical patient. However, asymmetry was significantly reduced in all the patients ($N = 6$). Here, mutual entrainment with a positive target phase difference (0.25 rad) was used to accelerate the walking rhythm on the affected leg side, and a negative target phase difference (−0.25 rad) was set to decelerate the walking rhythm on the unaffected leg. These results suggest that interpersonal mutual entrainment is effective in restoring symmetry during walking on hemiplegia patients.

Moreover, a type of developmental process that can be applied to rehabilitation was also observed. As shown in Fig. 2, both the human subject and the walking robot were restored to their original walking periods when cooperative walking was completed (mean period between 150 and 180 s, $T_h = 1.20$ s, $T_m = 1.12$ s). These original periods were close to each other as compared with those before cooperative walking (mean period between 30 and 60 s, $T_h = 1.24$ s, $T_m = 1.00$ s), suggesting that this interaction is not a simple mutual entrainment but a process including "mutual adaptation" of the natural frequency of walking period. As a result, dynamic stability of walking as measured by fluctuations in the walking period was retained even after cooperative walking (mean fluctuation $F_h = 0.024$ s (90–120 s), $F_h = 0.024$ s (150–180 s), two-tailed t-test, $t(46) = 0.09$, $P = 0.93$), as shown in Fig. 2. This phenomenon was also observed in hemiplegia patients, as shown in Fig. 5(b). A small fluctuation in walking period observed during cooperative walking still remained after stopping it (mean fluctuation $F_h = 0.050$ s (120–180 s), $F_h = 0.059$ s (180–240 s), two-tailed t-test, $t(98) = 1.04$, $P = 0.30$). These results suggest the dynamic stability of walking is sustained even after completing the cooperative walking with Walk-Mate. This type of adaptive property is an effective means to support rehabilitation. If we could further sustain this dynamic stabilization, then patients could walk without Walk-Mate after completing their rehabilitation using this system.

C. Conclusion

In this study, a human–robot interaction system based on mutual entrainment of walking rhythms was constructed to clarify the mechanism of interpersonal synchronization, and we demonstrated its potential applications to provide walking support of patients with gait disturbance. Although further systematic clinical evaluation is needed, the significance of this dynamic walking support based on mutual entrainment should be emphasized. Moreover, to improve the effectiveness of the present system, interaction between the virtual robot and human should be extended to include actual robots and human subjects. One possibility is a power assist robot system for walking. We have already started developing a robotic system using this dynamic interaction [37] and have demonstrated its usefulness in helping to support patients who cannot walk by themselves. We anticipate that this new framework will have vast potential applications not only to rehabilitation robots but also to a wide range of embodied and social communications for human–robot interaction [35], [36].

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REFERENCES

[1] J. D. Matarazzo, G. Saslow, A. N. Wiens, M. Weitman, and B. V. Allen, "Interviewer head nodding and interviewee speech durations," *Psychother.: Theory, Res. Pract.*, vol. 1, pp. 54–63, 1964.

[2] W. S. Condon and L. W. Sander, "Neonate movement is synchronized with adult speech: Interactional participation and language acquisition," *Sci.*, vol. 183, pp. 99–101, 1974.

[3] C. Nagaoka, M. Komori, and S. Yoshikawa, "Embodied synchrony in conversation," in *Conversational Informatics: An Engineering Approach*, T. Nishikawa, Ed. New York: Wiley, 2007, pp. 331–351.

[4] J. Piaget, *Play, Dreams, and Imitation in Childhood*. Milton Park, U.K.: Routledge, 1951.

[5] M. D. Jasnow and S. Feldstein, "Adult-like temporal characteristics of mother-infant vocal interactions," *Child Dev.*, vol. 57, pp. 754–761, 1986.

[6] E. Thelen and L. B. Smith, *A Dynamic Systems Approach to the Development of Cognition and Action*. Cambridge, MA: MIT Press, 1994.

[7] A. T. Winfree, *The Geometry of Biological Time*. New York: Springer-Verlag, 1980.

[8] Y. Kuramoto, *Chemical Oscillations, Waves and Turbulence*. New York: Springer-Verlag, 1984.

[9] S. Strogatz, *SYNC: The Emerging Science of Spontaneous Order*. New York: Theia, 2003.

[10] T. Muto and Y. Miyake, "Analysis of the co-emergence process on human-human cooperative walk," *Trans. Soc. Instrum. Control Eng.*, vol. 40, pp. 554–562, 2004 (in Japanese).

[11] S. Grillner, "Neurobiological bases of rhythmic motor acts in vertebrates," *Sci.*, vol. 228, pp. 143–149, 1985.

[12] A. H. Cohen, P. J. Holmes, and R. H. Rand, "The nature of the coupling between segmental oscillators of the lamprey spinal generator for locomotion: A mathematical model," *J. Math. Biol.*, vol. 13, pp. 345–369, 1982.

[13] N. Koppel and G. B. Ermentrout, "Coupled oscillators and the design of central pattern generators," *Math. Biosci.*, vol. 90, pp. 87–109, 1988.

[14] J. A. Scot Kelso, *Dynamic Patterns: The Self-Organization of Brain and Behavior*. Cambridge, MA: MIT Press, 1995.

[15] H. Yuasa and M. Ito, "Coordination of many oscillators and generation of locomotory pattern," *Biol. Cybern.*, vol. 63, pp. 177–184, 1990.

[16] G. Taga, Y. Yamaguchi, and H. Shimizu, "Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment," *Biol. Cybern.*, vol. 65, pp. 147–159, 1991.

[17] G. Taga, "A model of the neuro-musculo-skeletal system for human locomotion," *Biol. Cybern.*, vol. 73, pp. 97–111, 1995.

[18] J. A. Hall, J. A. Harrigan, and R. Rosenthal, "Nonverbal behavior in clinician-patient interaction," *Appl. Prev. Psychol.*, vol. 4, pp. 21–37, 1995.

[19] M. Hasegawa and K. Wada, personal communication, 2007.

[20] J. E. Pratt, B. T. Krupp, C. J. Morse, and S. H. Collins, "The RoboKnee: An exoskeleton for enhancing strength and endurance during walking," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2004, pp. 2430–2435.

[21] H. Kawamoto, S. Lee, S. Kanbe, and Y. Sankai, "Power assist method for HAL-3 using EMG-based feedback controller," in *Proc. Int. Conf. Syst., Man Cybern.*, 2003, pp. 1648–1653.

[22] Y. Miyake and H. Shimizu, "Mutual entrainment based human-robot communication field," in *Proc. IEEE Int. Workshop Robot Hum. Commun.*, 1994, pp. 118–123.

[23] Y. Miyake, G. Taga, Y. Ohto, Y. Yamaguchi, and H. Shimizu, "Mutual-entrainment-based-communication-field in distributed autonomous robotic system: Autonomous coordinative control in unpredictable environment," in *Distributed Autonomous Robotic Systems*, H. Asama, T. Fukuda, T. Arai, and I. Endo, Eds. Tokyo, Japan: Springer-Verlag, 1994, pp. 310–321.

[24] Y. Miyake and T. Miyagawa, "Internal observation and co-generative interface," in *Proc. IEEE Int. Conf. Syst., Man, Cybern.*, 1999, pp. 229–237.

[25] Y. Miyake, T. Miyagawa, and Y. Tamura, "Man-machine interaction as co-creation process," *Trans. Soc., Instrum. Control Eng.*, vol. E-2, pp. 195–206, 2004.

[26] G. Orlovsky, T. G. Deliagina, and S. Grillner, *Neural Control of Locomotion: From Mollusk to Man*. Oxford, U.K.: Oxford Univ. Press, 1999.

[27] A. Shumway-Cook and M. Woollacott, *Motor Control: Theory and Practical Applications*. Baltimore, MD: Williams & Wilkins, 1995.

[28] Y. Miyake, Y. Onishi, and E. Pöppel, "Two types of anticipation in synchronous tapping," *Acta Neurobiol. Exp.*, vol. 64, pp. 415–426, 2004.

[29] K. Takano and Y. Miyake, "Two types of phase correction mechanism involved in synchronized tapping," *Neurosci. Lett.*, vol. 417, pp. 196–200, 2007.

[30] S. Brunnstrom, *Movement Therapy in Hemiplegia: A Neurophysiological Approach*. New York: Harper & Row, 1970.

[31] J. M. Housdorff, "Is walking a random walk?: Evidence for long-range correlations in stride interval of human gait," *J. Appl. Physiol.*, vol. 78, pp. 349–358, 1995.

[32] D. Mestre, O. Blin, and G. Serratrice, "Contrast sensitivity is increased in a case of nonparkinsonian freezing gait," *Neurol.*, vol. 42, pp. 189–194, 1992.

[33] M. H. Thaut, G. C. McIntosh, R. R. Rice, R. A. Miller, J. Rathbun, and J. M. Brault, "Rhythmic auditory stimulation in gait training for Parkinson's disease patients," *Movement Disorder*, vol. 11, pp. 193–200, 1996.

[34] J. Perry, "The mechanics of walking in hemiplegia," *Clin. Orthop.*, vol. 63, pp. 23–31, 1969.

[35] K. Dautenhahn, "Getting to know each other: Artificial social intelligence for autonomous robots," *Robot. Auton. Syst.*, vol. 16, pp. 333–356, 1995.

[36] C. Breazeal, "Toward social robots," *Robot. Auton. Syst.*, vol. 42, pp. 167–175, 2003.

[37] Honda Motor Co., Ltd. (2008). [Online]. Available: http://www.honda.co.jp/news/2008/c080422.html