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Dual-Hierarchical Control Mechanism of Interpersonal Embodied Interactions in Cooperative Walking

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Interpersonal embodied interactions play a significant role as emergent functions in human development and rehabilitation. However, a framework for applying embodied interactions to "human interface systems" to support such emergent functions has not yet been suggested because the details of the motor-control mechanism have not yet been clarified. In this study, the interpersonal cooperative walking motions of two humans, as an example of such a mechanism, have been replicated and their motor-control mechanisms analyzed. The results indicate that the hierarchical dynamics were derived from an interpersonal footstep entrainment process and an intrapersonal interaction of arm and footstep motions. We suggest that embodied interactions in cooperative walking are achieved by a dual-hierarchical control structure related to emergence of the phase-control function of interpersonal cooperative walking, based on an automatic control mechanism for interpersonal entrainment of footstep motions and an intrapersonal voluntary-motion-control mechanism.

Keywords: embodied interaction, cooperative walk, motor control, entrainment, voluntary attention

1. Introduction

The interpersonal embodied interactions observed in human communication are believed necessary for human development. Piaget observed that infants engage in two types of actions – adapting their own motion to that of another person and letting the other person adapt his/her motion [1]. He suggested that interpersonal embodied interactions are related to the development of the infant's cognitive functions. Other studies reported that in face-to-face communication between two members of the opposite sex, one member's arm movements synchronize with those of the other member, implying that synchronizations in movement reinforce the semantic aspects of courtship [2, 3]. Perfetti and Castelfranch et al. focused on the interactive process between a handicapped person and their therapist in rehabilitation, and suggested that cooperative movements contribute to successful rehabilitation [4–6]. Perfetti then put his "cognitive therapeutic exercise," based on interpersonal embodied interactions, into practice [7]. Bunt and Goto et al. reported that encouraging handicapped children to perform impromptu musical performances, according to their motor abilities, actually improved their physical capabilities [8, 9]. These findings imply that embodied interactions between the therapist and the handicapped person improve motor functions.

To clarify the mechanism of interpersonal embodied interactions, we chose rehabilitation of the handicapped as a typical example of this interaction and focused our studies on cooperative movements between therapist and patient [10, 11]. We investigated the motor-control mechanism of mutual adaptation processes of footstep interaction in a cooperative walk between two humans, based on the interaction between a therapist and a handicapped person, from the neurophysiological point of view [12].

In the context of interpersonal cooperation in motion, an automatic synchronization phenomenon called mutual synchrony or entrainment has been studied. These studies [13, 14] reported that this phenomenon is observed in mother–infant communications and in face-to-face dialogs between adults. Schmidt et al. applied the HKB model, which is an autonomous heterarchical model of rhythmic coordination between two movements, to the interpersonal coordination of periodic movement by observing interpersonal visual coordination during oscillations of hand-held pendulums [15, 16]. With regard to interpersonal cooperation in walking, Ducourant et al. reported imitation processes in face-to-face walking [17], and Zivotofski & Hausdorff analyzed the relationship between interpersonal synchronization in walking and types of mediate information [18]. However, these studies have only reported synchronization phenomena without taking account of the neurophysiological point of view; a concrete motor-control mechanism has therefore yet to be identified.

The motor mechanism of human embodied interactions has been studied by psychological methods using voluntary actions within a controlled environment.

These studies focused primarily on the intrapersonal, dual-hierarchical motor-control mechanism of repetitive coordinated movements. Mates & Poeppel observed a task in which finger-tapping motions were synchronized with periodic auditory stimuli and suggested the existence of a mechanism that changes the dynamic patterns of the two motions [19]. Thelen & Smith, and Taga have also suggested a hierarchical control mechanism by observing the development of an infant's reaching movements, using its upper-limb movements and gait motion [20, 21]. However, their studies did not address the motion-control mechanism in interactive environments. The motor-control mechanism of interpersonal embodied interactions has not been studied in depth, in particular, the relationship, from the physiological point of view, between the automatic interpersonal synchronization mechanism and the voluntary hierarchical motor-control mechanism. This study therefore attempts to clarify the connection between, and the functional significance of, these two mechanisms, based on the assumption that interpersonal cooperative movement is achieved by these two motor-control mechanisms.

We chose cooperative walking between two humans as an example of interpersonal cooperative movement, analyzing the motion in terms of the automatic synchronization mechanism and the dual-hierarchical motor-control mechanism to clarify their inter-relationship. Based on the theory that arm-swing affects voluntary gait movement [22], we assumed that the arm-swing in walking is related to voluntary hierarchical motor-control and clarified its control mechanism by measurement of footsteps and arm-swing movements.

2. Methodology

In the experiments presented here, we measure the motor-control processes of an interpersonal cooperative walk and analyze the mechanism of these processes. First, we analyze the hierarchical motor-control processes in the interpersonal cooperative walk, measuring footsteps and arm-swing as the motor elements of locomotion. We then discuss the relationship between these hierarchical motor-control processes and voluntary motor-control, using the dual-task method.

2.1. Task

Four naive subjects (A, B, C, and D; male, healthy, native Japanese in their 20s) participated in this study as volunteers; the heights of the subjects were 175.2, 170.1, 178.2, and 176.5 cm, respectively. Six groups, with two persons per group, were formed to perform every combination of the cooperative walk. (Each subject walked three times, once in each combination.) In each session, subjects had enough break time to rest. In all cases, we asked the subjects to walk along a circular track (radius 5 m) in a quiet room at their usual walking speed. The track was indicated by a 50-mm-wide tape upon which the subjects were requested to walk. During the cooperative walk, each of the subjects was in a separate room and was asked to concentrate on the sound of the footsteps of the other person, which they heard over headphones, and to synchronize his own footsteps with his partner's footsteps, without any visual information about the other person.

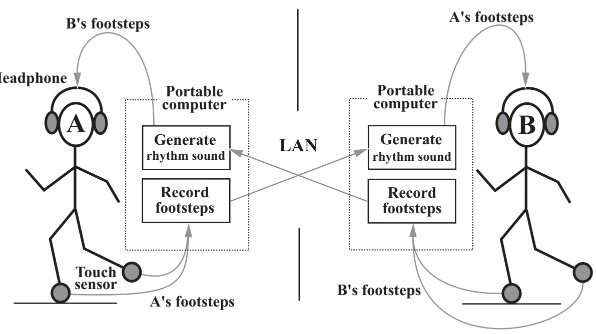

Fig. 1. Cooperative walk system.

2.2. Cooperative Walk System

To measure the cooperative walking motion, we focused on the sound of the footsteps and developed a system to enable mutual adaptation of walking through rhythmic sound. Our system is shown in **Fig. 1**. Touch sensors (OT-NO-1, OJIDEN, Osaka, Japan) placed under the heels of the subjects' shoes to measure their footsteps. Portable computers (Libretto70, TOSHIBA, Tokyo, Japan) record their steps and transfer them to the other subject's portable computer via a TCP protocol on a wireless local area network. When this reaches the other subject's portable computer, he hears the walking rhythms of his partner. The sound volume is adjusted individually for comfort. The delay between the actual step and transmission of the sound via headphones to the other subject is less than 0.01 s.

2.3. Measurement System

In human locomotion, the swinging motions of the upper limbs together with the stepping motions of the legs maintain the balance of the trunk [23, 24]. In our study, we regarded these as the main characteristic elements of the cooperative walk and measured these two elements. Only the right-hand side was measured because of bilateral symmetry.

The footsteps were measured by touch sensors (OT-NO-1, OJIDEN, Osaka, Japan) attached to the subject's heel, and the arm-swings were measured by an angular sensor (EG 511H, NIHON KOHDEN, Tokyo, Japan). Eke-Okoro et al. reported that a walker's gait tempo with the elbow joints straightened is significantly slower than normal [25]. Surprisingly, the tempo with fixed shoulders in addition to straightened elbows is not slower. This report suggests that shoulder rotation is adapted to lower-limb movement via the elbow joints. We measured

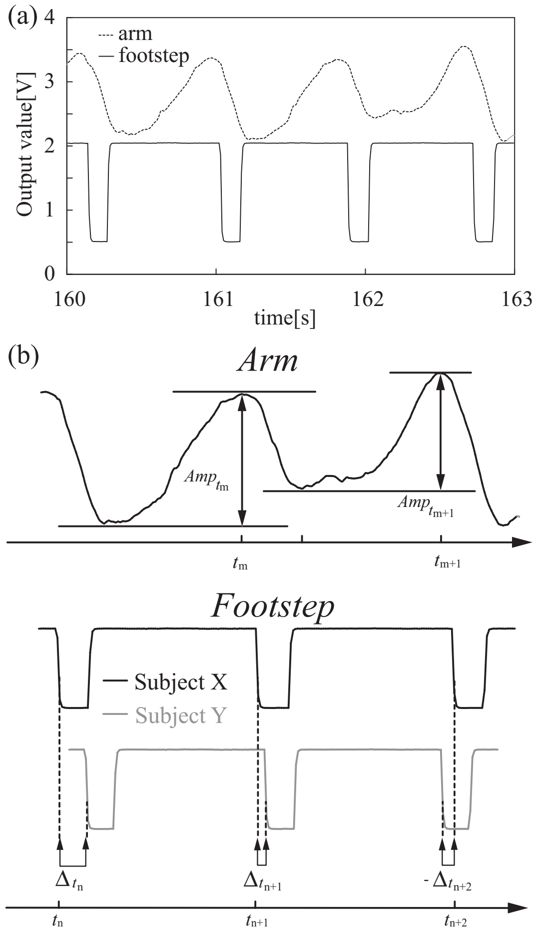

Fig. 2. (a) An example of the measured data. (b) Definition of the parameter values for the analysis.

the amplitude of the elbow angular oscillation to analyze upper-limb motion. These data were sent to a telemeter (WEB-5000, NIHON KODEN, Tokyo, Japan) by a transmitter (ZB-5812, NIHON KODEN, Tokyo, Japan) and converted with 128 Hz into discrete voltage data, which were recorded in a PC (ThinkPad 570, IBM, Westchester, NY, USA) through an A/D converter (AXP-AD02, ADTEK, Yokohama, Japan). **Fig. 2(a)** shows an example of the measured data. The footstep data were recorded as the time difference Δt_n between the times t_n when a cooperative walker's measured voltage dipped, as shown in **Fig. 2(b)**.

The arm motions measured by the voltage changes are proportional to the angular value. The value 0 V corresponds to a straight elbow. The value increases as the elbow flexes. The amplitude of the arm's angular oscillation is shown in **Fig. 2(b)**. The amplitude of the elbow's angular oscillation (the arm motion) is defined as the difference between the maximum peak of the voltage oscillation and the minimum peak just before that maximum. The value n or m in **Fig. 2(b)** shows the time sequences of the peaks.

2.4. Dual-Task Method

The motor center related to the control of walking is classified into the following two systems: a) the lower-level nervous system in the spinal cord and brain stem, controlling reflex and involuntary automatic movements, and b) the higher-level cerebral nervous system, controlling voluntary movements [26, 27]. The latter relates in particular to voluntary attention to surroundings, thus playing an important role in the mutual adaptation of walking motions between two individuals. We therefore controlled voluntary attention during the cooperative walk to clarify the relationship between the cooperative walk and voluntary motor-control. The attention condition was defined as a 60-s cooperative walk with a five-word-memorization task, which requires voluntary attention.

This is called the "dual-task" method [28]. This method aims to reduce the processing ability for the primary task (cooperative walk) by making subjects perform a secondary task (memorization task). Generally, such short-term (ca. 1 min) memorization is achieved by information processing in the working memory; this is called maintenance rehearsal [28–32]. Therefore, if a difference between the conditions with and without the memorization task is found, some of the cooperative walking motion should be subject to a mechanism controlled by voluntary attention.

The details of the memorization task are as follows. Prior to the cooperative walk, the subjects were shown five words composed of 3–5 Mola Hiragana or Katakana (Japanese letters), for 3 s, on a computer display. Immediately thereafter, they started the cooperative walk, while committing these words to memory. After walking, the subjects were immediately asked to repeat the words they had memorized before the walk.

3. Result #1

3.1. Footsteps and Arm-Swings During the Cooperative Walk

Each group of cooperative walkers walked for 600 s. **Fig. 3(a)** shows part of the data on the temporal development of the cooperative walkers' (subjects A & B) arm-swings and the time differences between the cooperative walkers' footsteps. The time differences between the footsteps of the two cooperative walkers tended to decrease after 340 s. This implies that the subjects decreased the time differences of their footsteps during a synchronization process. The arm-swings also developed dynamically. To evaluate the changes in the interaction between arm-swings and footsteps, we show an example of the changes in footstep values, named footstep coherence, and the fluctuating values of arm-swing amplitudes, called arm fluctuation, as shown in **Fig. 3(b)**.

In the figure, the relationship between the subjects' footsteps during the cooperative walk was analyzed as the temporal development of the coherence of the footsteps;

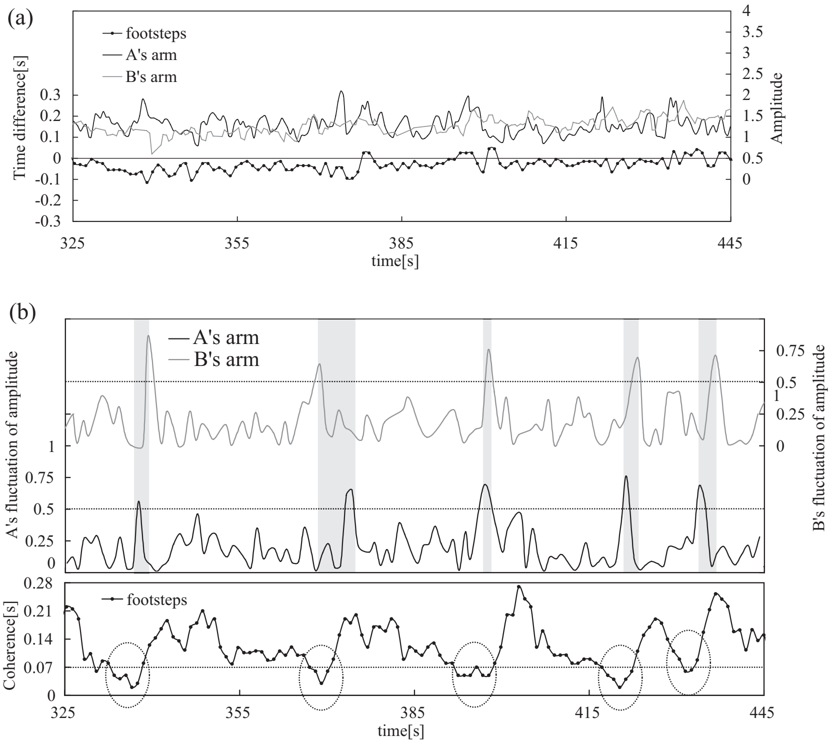

Fig. 3. (a) Angular amplitude of elbow-swings and time differences between cooperative walkers' footsteps. (b) Fluctuation of angular amplitude of elbow-swings and coherence of time differences between cooperative walkers' footsteps.

this is the smallest time difference Δt_n between each footstep of the cooperative walkers. In practice, we evaluated the coherence from the integration of the footstep fluctuations for at least 5 s (i.e., five steps) because the coherence should be distinguished from temporary decreases in fluctuations, as shown in Eq. (1).

$$Coherence_{t_n} = \sum_{k=n-4}^{n} |\Delta t_k - \Delta t_{k-1}| \quad . \; . \; . \; . \; . \; . \quad (1)$$

The arm dynamics were measured as the amplitude of the elbow's angular oscillations Amp_{t_m}. To cancel out individual differences, we standardized the data as $\overline{Amp}_{t_m}$ for the data for 600 s of single walking for each subject. The data was analyzed as the fluctuations shown in Eq. (2), defined on the same timescale, for comparison with the temporal development of coherence.

$$Fluctuation_{t_m} = |\overline{Amp}_{t_m} - \frac{1}{5} \cdot \sum_{k=m-4}^{m} \overline{Amp}_{t_k}| \quad . \quad (2)$$

At some points, we observed a tendency for significant fluctuations of the arm to increase by more than 0.5. This occurred cyclically at 10–30-s intervals. This was observed in both subjects, as well as in the interpersonal synchronization process between the temporal developments of peaks, with an error between 0.72 s and 4.95 s. To clarify this tendency, these peaks are indicated as gray in **Fig. 3(b)**. Moreover, when these phenomena occurred, the coherence of the walking period changed from a small value to a large value. To clarify the tendency of the arm-swing motion, the points that corresponded to a threshold value of 0.07 s are indicated by the dotted line. If the value was below the threshold, we regarded the point as significant. The dotted circle marks coherence, in which significant interpersonal fluctuations were observed in footsteps.

3.2. Interpersonal and Intrapersonal Arm-Swing and Footstep Processes

To evaluate the tendency found in the previous section quantitatively, we statistically analyzed the data for all the participants. We used a 120-s duration for the analysis, as every value of the coherence took less than 0.5 s, indicating a stable condition.

First, to estimate the tendency of interpersonal synchronization of arm-swings in all cooperative walkers, the subject's fluctuations in arm motions were shown as the upper black cells and the lower gray cells; these were plotted as the temporal development in units of 5 s for all groups of subjects, as shown in **Fig. 4(a)**. The figure shows a tendency for a subject's arm-swing fluctuations to occur close to the time of the other cooperative walker's arm fluctuations.

To study this tendency, the cross-correlation functions of the time-series data of the arm fluctuations of all the groups were calculated. The areas for analysis were divided into units of 5 s, which is the same timescale as the fluctuations observed, and a bit array that took 1 for a large arm-fluctuation and another bit array that took 0 for a small arm-fluctuation were made for calculating the

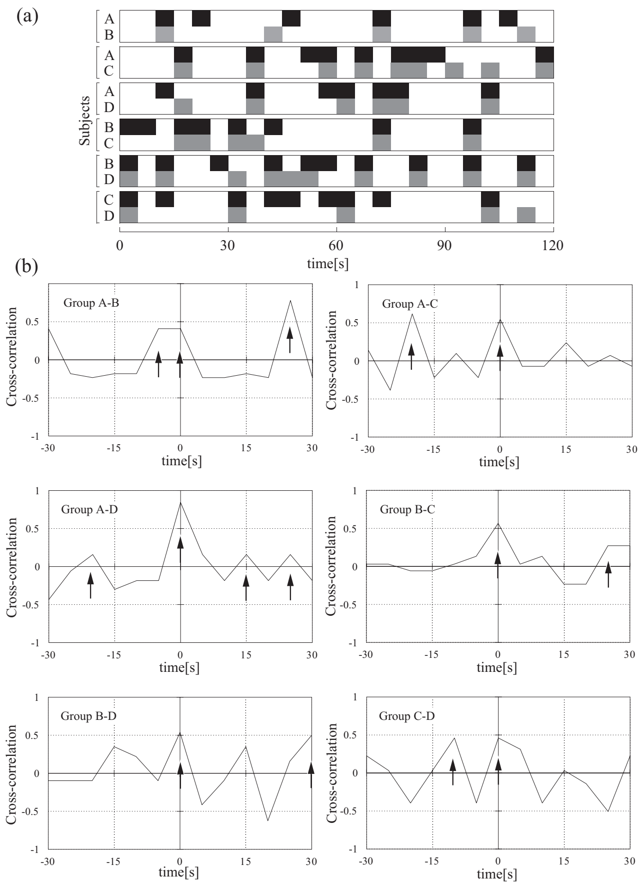

Fig. 4. (a) Temporal order of significant fluctuations in arm-swings during a cooperative walk. Black or gray marks indicate when the arm-swings fluctuate significantly in a time window of every 5 s. 66.7% of the marks are synchronized to the same timing as the other cooperative walker's marks, indicating phase synchronization of the fluctuations in arm-swings between the cooperative walkers in each pair. (b) Cross-correlation functions of the temporal data for the arm-swing fluctuations in the cooperative walk. The first- and second-highest peak points (black arrows) always include a time lag of 0 s. The time lag of 0 s shows significantly higher correlations than the other time lags (Mann–Whitney's U test, $z = 4.30$, $p < 0.0002$). This indicates a synchronization phenomenon in the temporal order of the arm-swing fluctuations between the cooperative walkers.

cross-correlation functions of all the groups to regulate the structure of the fluctuations.

Figure 4(b) shows the functions for all six groups. We found the peak functions at 0 s in four of the groups. Every cross-correlation value at 0 s was the first- or second-highest value, and significantly higher than the others. It became clear that both time series were almost perfectly synchronized with a time error of less than 5 s. The cooperative walkers achieved a mutual adaptive relationship in arm-swing through footstep interactions.

Secondly, to evaluate the intrapersonal process statistically, we compared the coherence of footsteps between the average of all measured data 5 s before and 5 s after the point of peak arm-fluctuation, as shown in **Fig. 5**. The re-

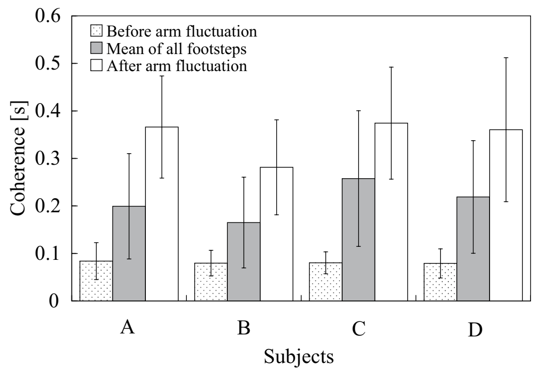

Fig. 5. Temporal development of footstep coherence in the cooperative walk. The mean values of the coherence, which are the fluctuations between the interpersonal timing of footsteps, show significant differences among the mean values of all footsteps and the footsteps before and after a significant arm-fluctuation. The trend indicates a temporal order in the change of coherence by arm-swing fluctuations (one-way ANOVA, $F(2,9) = 4.26$, $p < 0.00006$).

sults show that the footstep rhythm had a larger value just before and just after the large arm-fluctuation, and suggest that in the intrapersonal process, footstep coherence became more stable just before a significant arm-swing fluctuation and then became unstable just after this fluctuation.

3.3. Relationship Between Interpersonal and Intrapersonal Processes

The first tendency observed was interpersonal arm-swing synchronization. The second tendency, the intrapersonal process between footsteps and arm-swings, suggests that after a period of relative synchronization has been reached, a fluctuation in arm-swing synchrony occurs and is followed by a fluctuation in footstep coherence. Then, both arm-swings and footsteps tend to synchronize again. This suggests that an intrapersonal process achieves interpersonal adaptation.

Generally, human locomotion is organized by the stepping motion of the lower limbs and the swing motion of the upper limbs to maintain the balance of the body stem [23, 24]. We may therefore assume that arm-swing motion during walking can be controlled voluntarily to adapt the motion of the lower limbs. Interpersonal cooperation of human periodic movements such as gait has been regarded as the automatic control called "entrainment." However, since arm-swing is controlled voluntarily, these results suggest that there should be another process connected to voluntary control of motion of the lower limbs. Our results may suggest that interpersonal cooperative walking is achieved by a dual-hierarchical motor-control process, consisting not only of automatic control by entrainment, as described in conventional studies, but also by mutual adaptation processes connected to intrapersonal voluntary processes between arm-swings and footsteps.

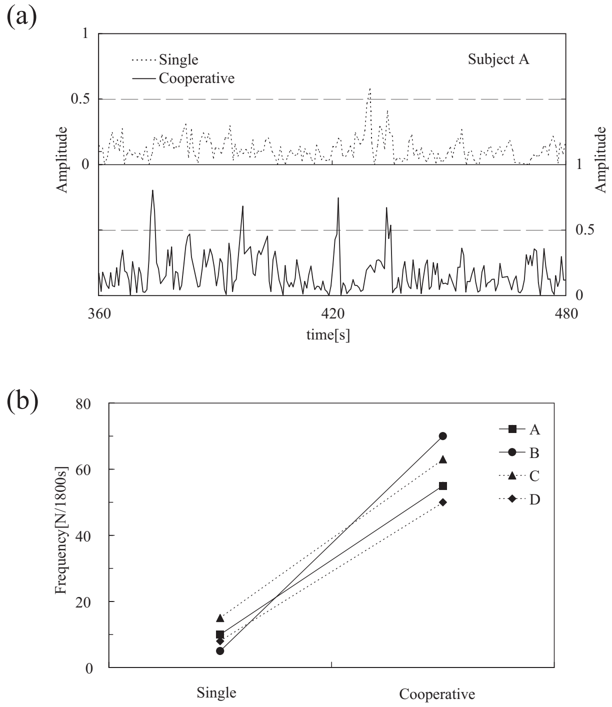

Fig. 6. (a) Temporal development of arm-swings in single and cooperative walks. Relative frequency of significant arm-swing fluctuations in the cooperative walk is higher than in the single walk. (b) The total frequency of arm-swing fluctuations in single and cooperative walks. The frequency in the cooperative walk is significantly higher than in the single walk (one-way ANOVA, $F(1,6) = 34.11$, $p < 0.003$).

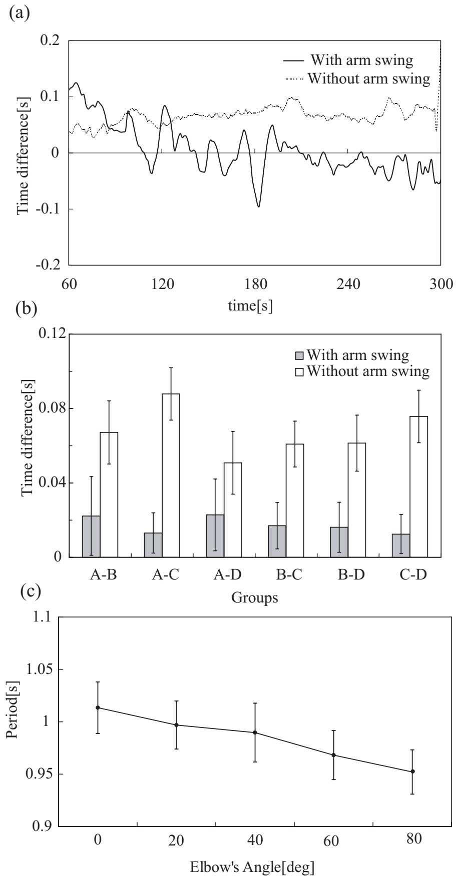

Fig. 7. (a) Temporal development of the time differences of footsteps in cooperative walk with arm-swings and without arm-swings. (b) Time differences of footsteps with arm-swings and without arm-swings. The mean value of each group with arm-swings has a smaller time difference than that without arm-swings. There is a significant difference between the two conditions (one-way ANOVA, $F(1,10) = 16.26$, $p < 0.003$). (c) Periods of footsteps with control of elbow-joint angle. We show the mean of the footstep period with the elbow-angle fixed at 0°, 20°, 40°, 60°, and 80°. There is a significant decrease in footstep period with increasing elbow-angle (one-way ANOVA, $F(4,15) = 3.06$, $p < 0.0003$).

4. Result #2

4.1. Relationship Between Hierarchical Process and Cooperative Motion in Walking

To compare the arm-swing data from a cooperative walk with those for a single walk, we measured a normal single walk, as the initial condition, with the same subjects and equipment as for the cooperative walk, but without sound. An example of the results, compared with the 600-s data for the cooperative walk, are shown in **Fig. 6(a)**. The number of significant fluctuations in arm-swings was larger in the cooperative walk than in the single walk. **Fig. 6(b)** shows the total frequency of significant fluctuations in arm-swings in three trials under both sets of conditions. It is clear that every subject's number of significant fluctuations was significantly larger in the cooperative walk. This suggests that large fluctuations in arm-swing are a characteristic of the cooperative walk.

We then measured the data for a cooperative walk with restriction of arm-swings to compare the hierarchical processes and the time differences between the two subjects' footsteps in the cooperative walk. This control condition was performed in the same manner as in the cooperative walk, but with arms folded tightly to restrict arm-swing.

In the non-restricted cooperative walk, the time differences between the two subjects' footsteps gradually decreased. In the restricted walk, we continued to see constant differences, as shown in **Fig. 7(a)**. To study this tendency quantitatively, we measured the synchronization differences during a 300-s cooperative walk with restriction of arm-swings, and compared these with the differences under non-restricted conditions in a 300-s cooperative walk, as shown in **Fig. 7(b)**. The results demonstrate that the synchronization differences under the restricted conditions were significantly larger than those under the non-restricted conditions. These results suggest that arm-swings are necessary for reduction of the synchronization differences between the cooperative walkers' footsteps. From the viewpoint of a dynamic system, the results also suggest that the angular oscillating motion of the elbow in arm-swings helps to control the characteristic frequency of gait rhythms, as the parameter characterizing such a periodic dynamic system is generally its characteristic frequency.

To verify this possibility, we measured the footsteps in a single walk with the elbow fixed at different angles. This was performed in the same manner as in the single walk but with the elbows fixed at both sides by joint orthoses (SofTec Genu, Bauerfeind, Zeulenroda, Germany) with an unstretchable leather strap. The values of the fixed angles were controlled to five different conditions (0°, 20°, 40°, 60°, and 80°). At 0° the elbow is completely extended. Each of the four subjects walked once for 4 min under each elbow-flexion condition.

Figure 7(c) shows the average gait periods standardized by the average of the natural period (average of gait period for each subject, applied only to that subject) under the different conditions of controlled elbow-flexion. The results showed that the more flexed the elbow joints, the faster the gait rhythm, i.e., flexing of the elbow lowers the average walking period. These two results suggest that the dual-hierarchical motor-control process is connected to the phase control of footstep timing in the cooperative walk.

4.2. Relationship Between Hierarchical Process and Voluntary Motor-Control

To evaluate the relationship between hierarchical motor-control and voluntary motor-control, we analyzed the relationship between the intrapersonal process with unrestricted arm-swings and footsteps, and the effect of voluntary attention on voluntary motor-control. The cooperative walk with a memorization task served as the control condition. Each pair walked together for 60 s in each trial, and the data were compared with the 60 s normal (no dual task) cooperative walk. We focused on the changes in arm-swings and the differences in footstep timing between the cooperative walkers without the data for the first 10 s because we anticipated that the secondary task could interrupt the beginning of the walk.

Table 1 shows the mean of every subject's correct answers in the memorization task. The average percentage of correct answers was in the range 80–90%. We can therefore confirm that the subjects actually completed the task. We compared the two conditions (with and without the dual task) with respect to the frequency of significant fluctuations in arm-swings in the intrapersonal process, as shown in **Figs. 8(a)** and **(b)**. This demonstrates that the fluctuation frequency under the control condition (no dual task) was greater than that under the experimental condition (dual task). These results imply that arm-swing fluctuations are related to voluntary attention. This suggests that voluntary attention is necessary for achieving the intrapersonal process between arm-swings and footsteps.

To analyze the footstep dynamics, we calculated the auto-correlation functions of all subjects' footstep time differences between lag 0 and lag 10, using the method shown in **Fig. 2(b)**. The averages and standard errors are shown in **Fig. 9(a)**. The timescale of 1 lag is regarded as almost 1 s because the average walking period in the cooperative walk is 1.07 s (normal condition: mean = 1.06 s, SD = 0.03 s; attention condition: average = 1.08 s, SD = 0.03 s). Measurements were taken from 10 s to 60 s during the cooperative walk, i.e., a total duration of 50 s. There were no significant correlations and no significant differences between the normal condition (no dual task) and the experimental condition. This implies that the dynamics of the temporal development of footsteps are relatively independent, and do not have characteristic structures.

To analyze the arm-swing dynamics, the auto-correlation functions of the angular amplitudes of of the arm-swings of all the subjects were calculated in the same way as for the footsteps. The auto-correlation was calculated from lag 1 to lag 10, as shown in **Fig. 9(b)**. The results show that the auto-correlation coefficient under the

Table 1. Percentage of correct answers.

Subject	Correct answers[%]
A	86.67
B	90.00
C	96.67
D	90.00
Mean	90.83

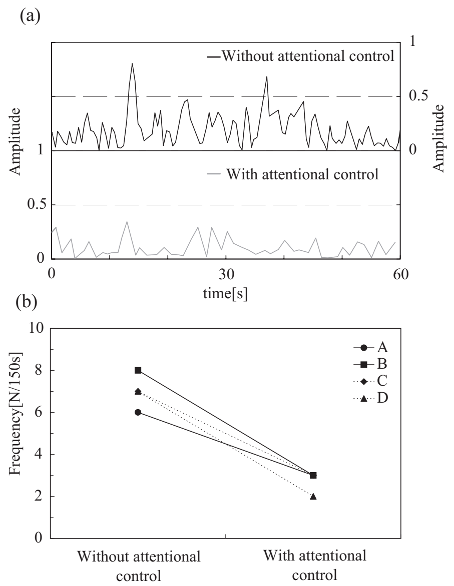

Fig. 8. (a) Temporal development of arm-swing motion with and without attentional control. (b) Frequency of arm-swing fluctuations in cooperative walk without and with attentional control. Here the total frequency of the arm-swing fluctuations (3 h 50 s) is shown under both conditions. The frequency with attentional control is significantly lower than that under the control condition (one-way ANOVA, $F(1,6) = 13.75$, $p < 0.0002$).

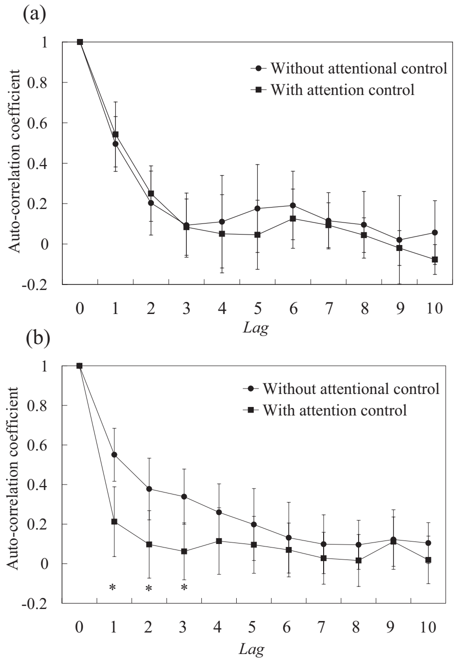

Fig. 9. (a) Auto-correlation of footstep time differences and arm-swing amplitudes. There is no significant difference in the footstep time differences with and without attentional control (Welch's t-test, $p > 0.16$). (b) There are significant differences in lag 1 to lag 3, marked by *, for the arm-swing amplitudes (Welch's t-test, lag 1 to lag 3: $p < 0.02$, lag 4 to lag 10: $p > 0.16$).

normal condition was higher than that under the experimental condition. In addition, a significant difference was only observed between lag 1 and lag 3, marked by *. Thus, arm-swing dynamics, in contrast to footstep synchronization, are influenced by voluntary attention (e.g., the secondary task in the dual-task method) during the first 1–3 s.

These results suggest that arm-swing during ambulation is controlled by voluntary attention and that the control mechanism is different from that for footsteps. Together with Result #1 in the previous section, this result suggests that the intrapersonal process connected with phase control of gait rhythm in the cooperative walk is achieved.

Pellecchia et al. reported that the phase coordination of rhythmic movement would be interrupted by changing the dynamics parameters during attentional control [33]. Based on this report, we suggest that our attentional control constrained the mechanism that controls movement of the elbow-joint; this movement is connected to the characteristic frequency of the arm-swing motion related to phase control of footstep rhythms. The dual-hierarchical, motor-control process is achieved not only by the interpersonal entrainment of footstep rhythms (automatic motor-control), but also by voluntary phase-control, related to voluntary attention, with intrapersonal motor-control between arm-swings and footsteps.

5. Discussion

Cyclic and automatic movements, such as walking, are generated by an oscillating mechanism in the spinal chord called the Central Pattern Generator (CPG) [34], with commands from a higher control mechanism located in the motor area in the cerebrum, the basal ganglia, and the mesencephalic locomotors region. We analyzed arm-swings and footsteps on the assumption that the CPG (as an automatic control system) mainly controls the rhythmic footsteps and the cerebrum mainly controls the voluntary control system and arm-swings.

In Result #1, we identified an interpersonal, mutual-adaptation process of synchronization between the frequencies in significant fluctuations in cooperative walkers' arm-swings. In the intrapersonal process, footstep coherence becomes more stable just before a significant arm-swing fluctuation and then becomes less stable just after the fluctuation. These two observations indicate that the timing of these interactions is synchronized between the interacting subjects.

Coherence in footstep interaction

$\Rightarrow$ *Significant arm-swing fluctuation*

Arm-swing fluctuation

$\Rightarrow$ *Controls coherence in footstep interaction*

In Result #2, to clarify the relationship between the dual-hierarchical, motor-control process and voluntary motor-control, and focusing on the intrapersonal temporal process between arm-swings and footsteps, we analyzed the mechanism from the viewpoint of voluntary movement. First, we found that the frequency of significant arm-swing fluctuations in the cooperative walk tended to be higher than in the single walk, suggesting that the intrapersonal process was characteristic of cooperative walking. We also discovered that elbow-joint control in arm-swings influences the characteristic frequency of the footstep rhythm. We measured the walking motion with restricted or fixed arm-swings. The results suggest that the intrapersonal process regulates phase control of gait rhythm in an interpersonal cooperative walk. Secondly, to clarify the relationship between voluntary control and hierarchical control, the frequency of significant arm-swing fluctuations in cooperative walking was measured during a dual task and compared with the frequency under normal conditions. Significant fluctuations, which characteristically had a timescale of 1–3 s, tending to be lower during the dual task. This means that the fluctuations should be observed for more than 3 s. Thus, with regard to the time structure, we can say that the arm-swing fluctuations in Results #1, evaluated on a timescale with 5-s units, must be same as the fluctuations controlled by the dual task. Only the arm-swings had dynamics which were controllable by the dual-task method. Voluntary attention was therefore necessary to generate arm-swing fluctuations. From these two results, it was clear that the hierarchical, motor-control process was achieved not only by

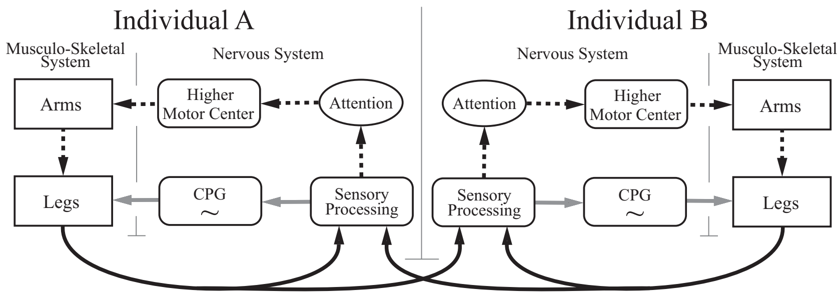

Fig. 10. Hierarchical control process in the cooperative walk.

interpersonal entrainment of footstep rhythms as the automatic motor-control, but also by voluntary phase-control with intrapersonal motor-control between arm-swings and footsteps. We therefore propose that the following dual-hierarchical motor-control mechanism controls the interpersonal cooperative walk, as shown in **Fig. 10**.

Interpersonal Control Process: automatic control based on entrainment of footsteps
The sensory process controlling gait (black arrow) is connected to the process controlling the musculo-skeletal system (gray arrow) through the low-level motor system.

Intrapersonal Control Process: mutual process of arm-swings and footsteps
The sensory process controlling gait (black arrow) is connected to the process controlling the coherence of footsteps by arm-swings (dotted arrow) through voluntary attention.

The CPG is an automatic control system that regulates rhythmic footsteps. It is well known that patients suffering from hemiplegia and injuries of the motor cortex, as well as patients with Parkinson's disease, caused by a dopamine metabolism abnormality, have characteristic gait disturbances [35, 36]. Mogenson reported that direct stimuli to a rat's hippocampus activated its gait motion [37]. These reports suggest the existence of a walking-control mechanism at the cerebral level. The intrapersonal control process addressed in this study is believed to be located there. However, our experimental results suggest that the intrapersonal control process is connected to the interpersonal control process. There have been reports that the motivation for and inauguration of walking motion are related to the limbic system and associated areas [38, 39]. However, the control process discussed in this paper is restricted to motion and does not address such processes.

Result #2 shows that the timescale of the interpersonal control process is about 1 s (**Fig. 9(a)**) because significant auto-correlations exceeding 0.5 were not observed, except in lag 1. The timescale of the intrapersonal cycle is 1–3 s because significant auto-correlations relating to voluntary attention were observed in lag 1 to lag 3. Result #1 also shows that the time required to synchronize with the other walker's gait is within a 10–30-s cycle. Result #2 suggests that the intrapersonal process is related to control reducing the synchronization differences in interpersonal footsteps. These results imply that the mutual adaptations of the cycle in the intrapersonal process generate a new cooperative function for controlling the phase of footstep rhythms.

The interpersonal control process is categorized as a feed-forward control process via the oscillating CPG; the duration is about 1 s at most. It is therefore very difficult to adapt to the other walker's conditions, which change for longer timescales. This kind of interpersonal cooperative movement, in particular, requires longer-term corrective functions to coordinate interpersonal walking motion because the two subjects are not applying exactly the same dynamics. Such functions can be realized as a self-modifying process that predicts the other walker's motion. This process enables the emergence of a function necessary for phase control of the footsteps in the above dual-control loop. These results suggest that the mutual connection between the inter- and intra-personal control processes are related to the emergence of a synchronized walking pattern.

6. Conclusion

This study analyzed the motor-control mechanism of a cooperative walk between two humans in terms of dual-hierarchical motor-control. The results suggest that the control was achieved by a connection between interpersonal automatic motor-control and intrapersonal voluntary control, i.e., by the interaction between the movements of the arms and legs with voluntary attention. The emergence of a phase-control mechanism was also suggested as the interpersonal mutual adaptation process. Assuming that perceived information with voluntary attention relates to non-autonomous control, such a hierarchical phase-control mechanism could be developed into a mathematical model using a previously reported method [40]: autonomous non-linear dynamics and non-autonomous dynamics with temporal development characteristics.

Some recent studies have attempted to confirm such interpersonal embodied interactions by using technical devices to achieve interpersonal entrainment [41–44]. However, the aim of these studies was to imitate the synchronization phenomenon. In the field of cognitive neurological science, the mirror neuron [45] or the bimodal neuron [46] can be modified through interaction with another person. However, these studies have never focused on the relationship between the functions of the neurons and interpersonal emergent mechanisms.

Concentrating on the emergent mechanism, we have proposed applying our model based on cooperative walking to a carer and handicapped person in the context of rehabilitation of gait disturbance. Thaut et al. used recorded music with a constant tempo, called RAS (Rhythmic Auditory Stimuli), to improve gait disturbance among Parkinson's disease and stroke patients [47, 48]. We have developed an interactive gait-support device, "Walk-Mate" [11], which uses dynamic periodic stimuli based on the patient's particular gait, and tested it on stroke patients [12]. The Walk-Mate contains a similar dual-hierarchical model [10] for controlling the walking tempo by entrainment of footstep interactions and phase-feedback control. We coordinated the phase differences of the user's footstep rhythms with a target value and consistently observed gait improvement when walking with the Walk-Mate [12].

This experiment only investigated the emergence of phase control in a cooperative walking paradigm. It is now necessary to focus on the role of the emergent system in, for example, gait rehabilitation, and clarify the mechanism of emergence in interpersonal embodied interactions. It is likely that the dynamics between a handicapped person and their carer in real gait training will be more asymmetric. The temporal development of phase dynamics in rehabilitation may therefore differ from the results described in this study. It is necessary to analyze interpersonal cooperation in gait training to understand the emergent mechanism and to develop and perfect a technical gait-training device as an actual technical application of the human-interface system.

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