Leg automaticity is stronger than arm automaticity during simultaneous arm and leg cycling

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HIGHLIGHTS

- Subjects performed simultaneous arm and leg cycling.
- Leg cadence variability was barely affected when the subjects attended to arm cycling.
- Arm cadence variability increased when the subjects attended to leg cycling.
- Automaticity of leg cycling is stronger than that of arm cycling.

ARTICLE INFO

ABSTRACT

Recent studies indicate that human locomotion is quadrupedal in nature. An automatic rhythm-generating system is thought to play a crucial role in controlling arm and leg movements. In the present study, we attempted to elucidate differences between intrinsic arm and leg automaticity by investigating cadence variability during simultaneous arm and leg (AL) cycling. Participants performed AL cycling with visual feedback of arm or leg cadence. Participants were asked to focus their attention to match the predetermined cadence; this affects the automaticity of the rhythm-generating system. Leg cadence variability was only mildly affected when the participants intended to precisely adjust either their arm or leg cycling cadence to a predetermined value. In contrast, arm cadence variability significantly increased when the participants adjusted their leg cycling cadence to a predetermined value. These findings suggest that different neural mechanisms underlie the automaticities of arm and leg cycling and that the latter is stronger than the former during AL cycling.

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1. Introduction

Humans have the ability to produce a variety of rhythmic arm and leg movements including crawling, walking, running, and cycling. These rhythmic and stereotyped motor outputs usually require minimal attention to joint movement. Many studies have performed behavioral and neurophysiological experiments that have demonstrated that the production of such rhythmic behaviors in quadrupedal animals strongly relies on the automaticity of localized networks of neurons or central pattern generators (CPGs) within the central nervous system [11,12,14,15,19,21,24]. Zehr and colleagues recently proposed an intriguing hypothesis that even in humans, rhythmic arm and leg movements are controlled by a CPG-like system [16,29,30]. It has also been suggested that neural control of rhythmic arm movements during human locomotion is regulated by a CPG-like system similar to that of the legs [5,31,32].

Although there are similarities in the neural control systems required for arm and leg cycling, differences between these systems

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have also been described. Carroll et al. [2] reported that cutaneous reflexes evoked in the right arm muscles were only weakly modulated while performing synchronous or asynchronous right and left arm cycling, active or passive right arm cycling, and left arm-only cycling. In contrast, reflexes evoked in a given leg were modulated by contralateral limb movements during leg cycling [3,4,18]. These findings suggest that there are different intrinsic properties of arm and leg automaticity. However, empirical data for differences in automaticity between the CPG-like systems controlling the arms and legs are rare. We previously demonstrated a clear difference between arm and leg automaticity; during simultaneous arm and leg (AL) cycling, the effect of an instant change in arm cycling cadence on that of leg cycling was negligible [26]. In contrast, arm cadence significantly decreased during an instant change in leg cycling cadence [26]. These behavioral observations suggest a neural interaction of the CPG-like systems that control cyclic arm and leg movement and that a CPG-like system for the leg may be dominant to that of the arm during AL cycling. However, it is still unclear whether the presumed dominance of the leg CPG-like system can be observed when subjects maintain stable AL cycling. We hypothesized that if CPG-like system automaticity of the leg is stronger than that of the arm, leg cadence variability might be smaller than that of arm cadence while performing AL cycling. To test this hypothesis, we examined variability in arm and leg cycling cadences during AL cycling while the participants focused their attention on either arm or leg cadence. Participants received visual feedback about arm or leg cadence during AL cycling and were asked to precisely adjust their cadences to a predetermined value. These experimental procedures allowed us to elucidate the differences in CPG-like system automaticity between the arm and leg.

2. Materials and methods

2.1. Participants

Eight neurologically intact male volunteers aged 22–34 years participated in this study. No participant had been involved in any cycle training programs. All participants provided informed consent according to the Declaration of Helsinki before participating in the experimental procedures. This study was approved by the local ethics committee, Faculty of Education, Chiba University.

2.2. Experimental procedures

The experimental ergometer setup was similar to that described in our previous study [26]. The arm ergometer (Matsushita, EU6210) was positioned in front of the participant, and the height of the axis of rotation was set at shoulder level so that the elbows were semiflexed (∼30°) when fully extended. The leg ergometer (COMBI, Power Max V) was positioned under the participants, and the axis of rotation was located 30 cm behind that of the arms and was adjusted so that the knees were semiflexed (∼30°) when fully extended. As there was no mechanical coupling between the ergometers for the upper and lower limbs, the participants could move both ergometers independently. The crank length was 15 cm for both ergometers. A photocell was attached to the arm and leg ergometers, and 8 TTL (transistor-transistor-logic) pulses were recorded for every rotation, which allowed us to calculate cycling cadence variability. The participants received visual feedback regarding arm and leg cadences from a monitor located in front of them.

2.3. Motor task

The participants performed AL cycling under two different conditions: (1) adjusting the arm cycling cadence and (2) adjusting the leg cycling cadence. The former required the participants to perform leg cycling at their preferred cadence while adjusting arm movement to target cadences (30, 45, or 60 rpm) with visual feedback displayed on a digital tachometer (Cocoreserach, KAZ-6512, Tokyo). After attaining the arm target cadence, the participants were instructed to continue AL cycling for 30 s. Participants received visual feedback for arm cadence throughout the motor task. In the second task, instructions for the "arm" and "leg" were switched. Each participant completed 5 trials at each cadence, for 30 randomly ordered trials.

2.4. Data analysis

The means, standard deviations (SDs), and coefficient of variations (CVs) of the cadences during 30-s AL cycling periods were calculated from the TTL pulses. Three-way repeated measures analysis of variances (ANOVAs) were performed to assess the effects of target cadence (30, 45, or 60 rpm), target limb (feedback for arm or leg), and moving limb (arm or leg) on CV modulation for cycling cadences and mean cycling cadence modulation. For post hoc comparisons, multiple pair-wise tests with Bonferroni corrections were performed. Significance was set at $p < 0.05$. Data are expressed as mean ± SD.

3. Results

Fig. 1 shows changes in arm and leg preferred cadence obtained from a single participant while adjusting arm (A) and leg (B) movement to target cadences. Leg cadence variability remained relatively constant during both tasks; however, variability of the preferred arm cadence while the participants adjusted leg movement to the target cadences was clearly increased compared to that of the arm while the participants adjusted arm movement to the target cadences.

Fig. 2 illustrates group means (±SD) of CV cadence during both tasks. Three-way ANOVA showed a significant interaction between target limb and moving limb ($F(1, 7) = 21.96$, $p < 0.01$). In addition, the interaction between target cadence and moving limb was significant ($F(2, 14) = 8.11$, $p < 0.01$). Two-way ANOVA was performed with target limb and moving limb in each target cadence. When participants adjusted the arm or leg to 30 rpm, there were significant main effects for target limb ($F(1, 7) = 21.99$, $p < 0.001$) and moving limb ($F(1, 7) = 17.89$, $p < 0.001$), and a significant interaction was found between them ($F(1, 7) = 13.90$, $p < 0.001$). Post hoc comparisons showed that arm cadence CV modulation while the participants adjusted leg movement to 30 rpm was significantly higher than that of the arm while the participants adjusted arm movement to 30 rpm ($p < 0.001$). Similar results were obtained while participants adjusted arm or leg movement to 45 or 60 rpm (both, $p < 0.001$).

Fig. 3 shows the group means (±SD) for arm and leg cadence while participants adjusted arm or leg movement to target cadences. Notably, participants correctly controlled arm or leg cadence in accordance with predetermined values. Preferred leg cadence showed a gradual increase in conjunction with an increase in arm cycling target cadence. Three-way ANOVA showed a significant interaction among target cadence, target limb, and moving limb ($F(2, 14) = 33.36$, $p < 0.001$). Two-way ANOVA was performed with target cadence and moving limb for each target limb. When participants adjusted arm movement to the target cadences, there were significant main effects for target cadence ($F(2, 14) = 116.08$, $p < 0.001$) and moving limb ($F(1, 7) = 10.70$, $p < 0.001$), and a significant interaction was found between them ($F(2, 14) = 12.70$, $p < 0.001$). Post hoc comparisons showed a significant difference in preferred leg cadence modulation when arm