Analysis of Rhythm Adjustment Mechanism of Human Locomotion against Horizontal Perturbation

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Abstract—Human locomotion is considered to be realized using rhythmic signal generated in central pattern generator (CPG). When perturbation is applied during locomotion, a mechanism that adjust the rhythm of CPG based on the timing of foot-contact or foot-lift, called ‘phase reset’ has been proposed and the contribution of such a mechanism on the stabilization has been indicated. In order to verify the existence of phase resetting mechanism, this research measured the human locomotion with perturbation and investigated the transition of rhythm after the perturbation. As a result, adjustment of motion rhythm terminated after foot-contact even the phase difference between after the termination and before perturbation remained. This result indicates the existence of CPG tuning i.e., phase reset. Present research further analyzed the rhythm adjustment of synergies by extracting synergy using singular value decomposition, and found no difference in phase characteristic among synergies. This result indicates the rhythm tuning does not work for each synergy but works on the rhythm generator.

I. INTRODUCTION

Walking is a cyclic motion actuated by the rhythm generated by the central pattern generator (CPG). The rhythm attracts the walking motion into stable cycle, which enables the walking with limited feedback control. Animals are considered to improve the stability by controlling the rhythm itself, such as resetting the rhythm by the timing of foot-contact and foot-lift [1]. The contribution of phase resetting for recovering the motion after the perturbation has been discussed using dynamical simulation [2], [3], and the improvement of the stability by phase resetting has been verified. In this way, phase resetting was implied to have an important role on the human walking control, the existence of such a mechanism on human walking has not been experimentally verified.

The walking rhythm has been estimated from measured motion using motion of specific point, such as toe or heel. While this calculation extracts the rhythm of local motion, recent researches have extracted a few principle rhythmic patterns that represent whole body motion using PCA[4]. The extracted rhythmic patterns are considered to represent the intersegmental coordination or synergy, and each patterns are possibly controlled. Both rhythm extracted from local (heel) motion and rhythm extracted from whole body motion are considered to be significant; such that the heel and toe motions are directly related to the event of foot-contact and foot-lift, and rhythm of synergy are more related to the walking control or the activity of central pattern generator.

Above all, this research measures the motion of walking human applying horizontal perturbation during locomotion, and calculates the transition of walking rhythm extracted based on 2 criteria, 1: heel-contact, and 2: temporal pattern of kinematic synergy. By investigating whether the entrainment into the rhythm remains after heel-contact or the entrainment terminate at the heel-contact by the effect of rhythm resetting, we discuss the existence of phase resetting mechanism for human locomotion.

II. MATERIALS AND METHODS

A. Experimental device and the procedure of experiment

Subjects walked on a treadmill with velocity 1.0[m/s]. Horizontal perturbation is applied to the subjects on the treadmill by changing the velocity of the treadmill with high acceleration. During the perturbation, treadmill speed increases (or decreases) until 1.0±0.3[m/s] within 0.1[s] and the velocity returns to 1.0[m/s] within following 0.1[s]. Subjects are 2 healthy males. They are required to look at a small circle which locates far front of the subjects and the motions of their joints were measured with a motion capturing system (MAC3D Digital RealTime System, Motion Analysis). Reflective markers were attached to the subjects’
skin overlying the following body landmarks of both hemi-
images: ear tragus, upper limit of the acromion, greater
 trochanter, lateral condyle of the knee, lateral malleolus, sec-
ond metatarsal head, and heel. The sampling rate is 500[Hz].
Duration of one measurement is 60[s], which starts after
the walking of subject is settled. The experiment is repeated
for 50 times for both forward and backward perturbations.
Subjects gave informed consent prior to data collection
according to the procedures of the Ethics Committee of
Doshisha University.

B. Data preparation

Recorded time series of joint positions are low-path fil-
tered with cutoff 20[Hz] 2nd order butter-worth type filter.
The body angles are calculated for 7 segments defined on the
sagittal plane, as shown in Fig.2A. Every angle was defined as
an elevation angle, based on the knowledge that the elevation
angles behave more stereotypically than the relative angles
[4], [5].

The timing of foot-contact and foot-lift are defined to be
the time heel vertical position reaches minimum and the time
toe vertical position reaches minimum respectively, and both
timings are calculated from the recorded time series data.

C. Extraction of synergies using singular value decomposi-
tion

Kinematic synergy is a combination of segments mov-
ing in a similar manner, and thus can be extracted by calculating correlations of segmental movement. Our past
research applied singular value decomposition (SVD) to the
elevation angle of whole-body segment \( \theta(t) = [\theta_{\text{footR}}(t), \theta_{\text{thighR}}(t), \cdots]^T \in \mathbb{R}^{7 \times 1} \) during a full
sampling \( t = 1 \ldots \) number of sampling points: \( n_s \) of the
objective phase \( \Theta = [\theta_1(t), \theta_2(t), \cdots] \in \mathbb{R}^{7 \times n_s} \), and
extracted kinematic synergy and its temporal amplitude [6].

\[
\Theta = \Theta_0 + \sum_i z_i (\lambda_i v_i)^T, \quad (1)
\]

Here, \( \Theta_0 \in \mathbb{R}^{7 \times n_s} \) is constructed by repeating the temporal
average \( \theta_0 \in \mathbb{R}^{7 \times 1} \) of \( \Theta \) for the number of samplings
points \( n_s \), \( z_i \in \mathbb{R}^{7 \times 1} \), \( v_i \in \mathbb{R}^{n_s \times 1} \), and \( \lambda_i \in \mathbb{R}^{1 \times 1} \) are the right
and left singular vectors and the singular value of \( \Theta - \Theta_0 \)
for each.

The level of the singular value \( \lambda_i \) shows that over 99% of
the entire walking movement consists of three coordination
patterns \( (i = 1, 2, 3) \) [6]. Because \( z_i \) shows the coordination
among segments, it is refereed as kinematic synergy and
the temporal characteristic of synergy is represented by \( \lambda_i v_i \)
temporal patterns of \( v_i \) are shown in Fig.2C). In order to
discuss the response characteristic of the synergy against
perturbation, we analyze \( v_i \) for the motion after perturbation.

D. The value of phase shift

Phase shift generated by the perturbation is defined as
shown in fig.3A. If we write an average walking cycle is \( T_0 \),
last landing time before perturbation is \( t_{\text{land}0} \), and landing
time next to perturbation is \( t_{\text{land}1} \), next landing time \( t_{\text{land}0} \) is
written to be \( t_{\text{land}0} + T_0 \), so the time shift by the perturbation
becomes \( t_{\text{land}1} - (t_{\text{land}0} + T_0) \). The quantity of phase shift
\( \Delta \phi_{\text{land}} \) is a normalized time shift by walking cycle \( T_0 \), so
the phase shift is defined to be

\[
\Delta \phi_{\text{land}} = \frac{t_{\text{land}1} - (t_{\text{land}0} + T_0)}{T_0}. \quad (2)
\]

In the same manner, in order to study the phase shift of
each synergies, peak time of the temporal coordination right
before the perturbation is defined as \( t_{\text{mode}0} \) and peak time
right after the perturbation is defined as \( t_{\text{mode}1} \). Next peak
time of \( t_{\text{mode}0} \) is supposed to be \( t_{\text{mode}0} + T_0 \), if there were no
perturbation. So the time shift by the perturbation is \( t_{\text{mode}1} -
(t_{\text{mode}0} + T_0) \). Phase shift \( \Delta \phi_{\text{mode}} \) is normalized time shift by
walking cycle \( T_0 \), so it becomes

\[
\Delta \phi_{\text{mode}} = \frac{t_{\text{mode}1} - (t_{\text{mode}0} + T_0)}{T_0}. \quad (3)
\]
By applying perturbation for various phase, and by investigating the phase shift $\Delta \phi_{\text{land, mode}}$ against the phase of perturbation input $\phi_{\text{stim}}$

$$\phi_{\text{stim}} = \frac{t_{\text{stim}} - t_{\text{land0, mode0}}}{T_0},$$

we calculate the phase response curve of the walking motion.

E. Duration of walking cycles during and after perturbation

In order to study the recovering process of the motion phase after perturbation, we define the phase after perturbation as fig 3B. Landimg time of $k$th after perturbation is defined as $t_{\text{land}k}$. The quantity of change in the walking phase at $k$th walking cycle can be calculated by the duration of walking cycle. Normalized duration of $k$th walking cycle $D_{\text{land } k}$ is defined by the duration between $k$th landing time $t_{\text{land}k}$ to $k$th landing time $t_{\text{land}k+1}$ divided by average walking cycle $T_0$ as follows

$$D_{\text{land } k} = \frac{t_{\text{land}k+1} - t_{\text{land}k}}{T_0}.$$  (5)

Normalized cycle duration of synergies at the $k$th cycle after perturbation $D_{\text{mode } k}$ is also defined for analyzing the tuning of the synergistic motion. $D_{\text{mode } k}$ is defined as the duration between $k$th landing time and next peak timing of the mode after $T_{\text{land}k}$.

$$D_{\text{mode } k} = \left\{ \begin{array}{ll}
        \frac{t_{\text{land}k+1} - t_{\text{land}k}}{T_0}, & \text{if } t_{\text{mode } k} > t_{\text{land}k} \\
        \frac{t_{\text{land}k+1} - t_{\text{land}k}}{T_0}, & \text{if } t_{\text{mode } k} < t_{\text{land}k}
        \end{array} \right.$$  (6)

By calculating $D_{\text{land, mode } k}$ from the motion with perturbation at various phase, the recovery of phase against perturbation is investigated. $D_{\text{land, mode } k}$ of double and single support phase are separately calculated by taking attention to the effect of perturbation input phase, and change in $D_{\text{land, mode } k}$ with walking cycle $k$ is statically evaluated using ANOVA.

In order to numerically evaluating the phase shift remaining after the tuning of the motion, phase shift between the cycle before perturbation and enough cycle after perturbation is calculated. If $k$th cycle $t_{\text{land}k}$ is selected as after stabilized cycle, the phase shift until $k$th landing time is defined by comparing time $t_{\text{land}k}$ and $k$th after cycle with $T_0$ from $t_{\text{land}0}$, i.e. the time shift is $t_{\text{land}k} - (t_{\text{land}0} + kT_0)$. The phase shift of $k$th cycle after perturbation $\Delta \phi_{\text{land } k}$ is obtained by dividing the time shift with walking cycle $T_0$ such that

$$\Delta \phi_{\text{land } k} = \frac{t_{\text{land}k} - (t_{\text{land}0} + kT_0)}{T_0}.$$  (7)

III. RESULTS

A. Phase response curve

Fig.4 shows the phase response curve calculated based on the time of foot-contact. Fig.4A shows the result of forward perturbation by decelerating treadmill speed and fig.4B shows that of backward perturbation by accelerating treadmill speed. Fig.4A shows that the walking phase increases by forward perturbation representing phase lag of motion, and walking phase decreases by backward perturbation representing phase lead of motion. The quantity of phase shift changed depending on the input phase of perturbation, and the shift can be pointed out more dominantly during single support phase than double support phase.

Fig.5 shows the phase response curve of each synergy extracted by SVD. Phase lag by forward perturbation (Fig.5A) and phase lead by backward perturbation (Fig.5B) similar to the phase response curve of heel contact (Fig.4) can be found. The difference of the quantity of phase shift depending on the perturbation phase, i.e., phase shift was more dominant during single support phase than double support phase, was also pointed out. On the other aspect, an apparent difference in the characteristic of phase response curve among synergies cannot be found.

B. Change in cycle after perturbation

The recovering walking motion represented by the transition in walking cycle after perturbation is shown in fig.6.
Fig. 4. Phase response curve obtained at heel-landing. A: Forward perturbation generated by deceleration of belt speed. B: Backward perturbation generated by acceleration of belt speed. The perturbation area are separated with different colors into double and single support phases. Gray colored area labeled with DS signifies double support phase. White colored area labeled with SS signifies single support phase. SS(R) and SS(L) are single support phase with right support leg and left support leg respectively.

Fig. 5. Phase response curve obtained at peak timing of temporal coordination. A: Forward perturbation and B: Backward perturbation. The separation of perturbation phase is performed same manner with fig.4.

Fig. 6A shows the result of forward perturbation and Fig. 6B shows that of backward perturbation. Duration of the cycle including perturbation input (colored by black) of forward perturbation (Fig. 6A) was longer than the duration of 1 to 5 cycles after perturbation, and it was shorter than 1 to 5 cycles after perturbation in case of backward perturbation (Fig. 6B). These difference was more apparent during single support phase than double support phase. Compared to these differences in the cycle including perturbation, duration of 1 to 5 after perturbation were not mutually different. By testing the significance of the difference in length between the cycle including perturbation and 1 to 5 cycle after perturbation using ANOVA, only the cycle with perturbation was significantly different from following cycles (p < 0.05) during single support phase of both right and left leg stance about forward perturbation and right single stance phase about backward perturbation. The cycle with perturbation was also significantly different from 3 and 5 cycle after perturbation about the left stance phase about backward perturbation (p < 0.05). Moreover, the significant difference cannot be found among every 1 to 5 cycles. This result shows that even if the rhythm of motion is changed by the
perturbation and difference between the phase of the motion and rhythm generator is occurred, it does not affect to the following motion after heel contact.

In order to study the quantity of phase shift after the motion is stabilized, the phase shift after perturbation is calculated. Based on the previous result that the walking cycle does not change after at least 2 cycles after perturbation, the after stabilized cycle was set to be 2. Then the remaining phase shift at 2: $\Delta \phi_{\text{land}}$ was calculated. Table I shows the result of remained phase shift $\Delta \phi_{\text{land}}$ of stabilized motion after perturbation during single support phase. From the table, the walking phase prolonged for approximately 4 to

**Fig. 7.** Phase response curve obtained at peak timing of temporal coordination. A: the result of forward perturbation and B: the result of backward perturbation. The results are displayed with average and standard deviation. DS1, SS(R), SS(L) DS2 are the support phase of perturbation input with same meaning as described in fig.6.
difference between before and after perturbation (table I) indicates that the motion does not fully entrained into CPG.

The observed result concerning change in the walking cycle is illustrated in fig.8A, and the underlying mechanism concerning rhythm is estimated to be fig.8B. If there is no mechanism that affects the rhythm generated by CPG, the phase shift occurred in $D_{land0}$ will gradually reduce by the effect of entrainment into the rhythm of CPG, and it will not generate any phase difference between before after perturbation. Deletion of variation in cycle after perturbation ($D_{land1}$...$s$) and phase shift observed after stabilized cycle (Table I) implies the existence of rhythm tuning as shown in fig.8B.

Are there any relationship between intersegmental coordination and phase reset?

This research has evaluated the rhythm of motion, by separating motion at the event of heel contact and also separating with respect to each synergies. However, by comparing the result of phase response curve of synergy shown in fig.5 with that of whole motion shown in fig.4, and by comparing the result of the recovering process shown in fig.7 with that of whole motion shown in fig.6, there were no significant different. These results indicate that the phase reset does not significantly change the rhythm for particular synergy, but it directly affects the rhythm generator.

V. CONCLUSION

In order to elucidate the architecture of rhythm control mechanism during locomotion, we measured motion after perturbation and discussed the transition of rhythm by and after perturbation. From the result that the adjustment of rhythm against change in posture disappeared after the foot-contact, and the result that the phase shift caused by the perturbation remained after the termination of rhythm adjustment indicated that the central rhythm was also adjusted by the effect of mechanism referred as phase reset. Because phase characteristic was no different even the rhythm was decomposed into synergy, the adjustment of rhythm was considered to work directly the rhythm generator.

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