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An analysis of leg joint synergy during bipedal walking in Japanese macaques

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***Abstract*— We analyzed bipedal locomotion of Japanese macaques from the view point of leg joint synergy by the UCM (Uncontrolled manifold) analysis in order to examine how and when hip, knee and ankle joints cooperate so as to suppress the variances of the toe position relative to the hip position. Our results showed that joint synergy is exploited at some moments during walking. For instance, the variance of the vertical toe position was suppressed by joint synergy when the tip of the finger passes its lowest position from the ground. Some characteristics of the synergy pattern of macaques have been also reported in human walking, on the other hand, some differences between humans and macaques were found. For instance, high degree of joint synergy that suppresses the variance of hip height was observed around the end of stance phase in human walking, but such synergy was weak in macaques. The results suggest that different control strategies are used in bipedal walking of macaques and humans.**

I. INTRODUCTION

Erect bipedalism, such as human walking, is less stable than quadrupedalism and therefore, requires skillful motor control. In order to understand the control mechanism, the bipedal walking of trained Japanese macaques (*Macaca fuscata*) and their neural activities have been studied for ages by physiological experiments [1]. In fact, highly trained macaques show erect bipedalism, however, some differences between human walking and bipedal walking of the trained macaques have been reported from the view point of physical anthropology. For example, macaques extend the ranges of hip and ankle movements and acquire the ability to use the inverted pendulum mechanism in walking through training over several years, however, their knees never extend straight and the ankles never ground as observed in human walking [2], [3], [4]. It is also reported that the ground reaction force is single peaked, with no sign of the double-peaked curve observed in human walking [5]. Do these differences arise from the difference of the physical structures, i.e. musculo-skeletal systems, of macaques and humans, or are there any differences in control strategy?

We have analyzed the joint trajectories during human walking by the UCM (Uncontrolled manifold) method [6] and examined how the toe position relative to the hip position are controlled by joint synergy [7], [8]. The results suggest that the toe position are controlled by exploiting joint synergy at important points to realize stable walking, such as in kick off phase and at the moment when the toe passes its lowest position [8]. On the other hand, bipedal walking of macaques have not been studied from the view point of joint synergy.

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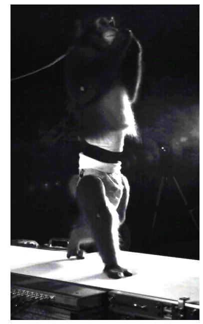

Fig. 1. Measurement of joint trajectories during walking

The purpose of this study is to examine how and when hip, knee and ankle joints are coordinated during bipedal walking of macaques and elucidate the difference of the underlying control scheme for walking of macaques and humans. For this purpose, we analyzed the variance of joint trajectories during walking of macaques by the UCM method and examined how the toe position relative to the hip position are controlled by joint synergy.

II. EXPERIMENTAL METHODS

The subjects were two Japanese macaques, KA and KU, that had been trained in bipedal walking for more than seven years (TABLE I). We measured the leg trajectories of the subjects who equipped reflective markers at the hip, knee, ankle and the fifth metatarsal head (toe), and walked on a treadmill at 4 km/hr. The trajectories were recorded by a motion capture system (HotShot 1280, Nac Image Technology, USA). Frame rate and shutter speed were set to 125 frames/s and 1/250 s. The trajectories were smoothed by a 6th-order low-pass Butterworth filter with the cutoff frequency of 6 Hz (Fig. 1).

In this study, we modeled a leg as a simple three-link system that moves in a vertical plane (Fig. 2), and analyzed the leg movement during walking as follows. Leg trajectory data of 17 strides of the subject KA and 10 strides of KU were divided into stance and swing phase and normalized by the duration of each phase. The average $\bar{\boldsymbol{\theta}}(t) = \left(\bar{\theta}_1(t), \bar{\theta}_2(t), \bar{\theta}_3(t)\right)^t$ of the normalized data was computed for each subject, where t is the normalized time

TABLE I

BODY PARAMETERS OF SUBJECTS

ID	Sex	Age (year)	Body weight (kg)	Length of the thigh (m)	Length of the lower thigh (m)	Length of the foot (m)
KA	M	10	12.3	0.178	0.179	0.067
KU	M	8	9.2	0.166	0.166	0.075

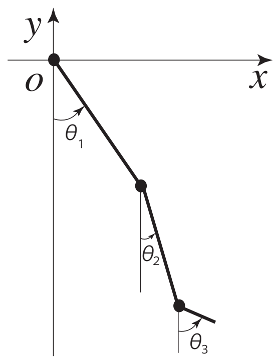

Fig. 2. Three-link leg model.

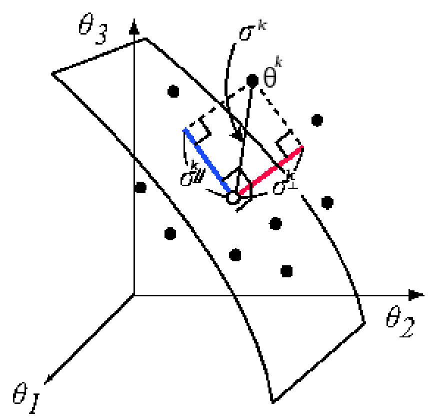

Fig. 3. Analysis of variance from the view point of the UCM. The axes show joint angles, the closed circles show joint angles $\boldsymbol{\theta}^k(t)$ at a specific time in a walking cycle $\boldsymbol{\theta}(t)$, the open circle shows the average $\bar{\boldsymbol{\theta}}(t)$ and the curved surface shows the UCM on which the horizontal toe position $(X(t))$ is constant. The projective lines, $\sigma^{\|}$ and $\sigma^{\perp}$, show the parallel and orthogonal components of the deviation of a joint data to the UCM, respectively. The former deviation does not change the toe position but the latter does.

and the subscript $i = 1$, 2, and 3 show the hip, knee and ankle, respectively. The distribution of the deviation of the joint angles $\boldsymbol{\sigma}^k(t) = \boldsymbol{\theta}^k(t) - \bar{\boldsymbol{\theta}}(t)$ was analyzed by the UCM method, where the superscript k indicates the k-th stride data (Fig. 3).

In the UCM analysis, we selected the joint angles as task variables and the horizontal and vertical toe position relative to the hip position as the performance variables. We summarize the method of the UCM analysis in the case when we select the UCM as the manifolds in the joint angle space on which the horizontal toe position $X(t)$ is constant.

The horizontal toe position $X(t)$ is a function of the joint angles:

$$X(\boldsymbol{\theta}(t)) = L_1 \sin(\theta_1(t)) + L_2 \sin(\theta_2(t)) + L_3 \sin(\theta_3(t)), \quad (1)$$

where L_1, L_2 and L_3 show the link length (Fig. 2). In this case, the UCM on which the horizontal toe position is constant is two-dimensional and the normal vector of the UCM is given by $\boldsymbol{\epsilon}_X^{\perp}(t) = \nabla_\theta X(\bar{\boldsymbol{\theta}}(t))$.

The parallel and orthogonal components of the deviation to the UCM, $\sigma_X^{\|}(t)$ and $\sigma_X^{\perp}(t)$, are given by

$$\begin{cases} \sigma_X^{\|}(t) &= \frac{1}{N} \sum_{k=1}^{N} |(\boldsymbol{\theta}^k(t) - \bar{\boldsymbol{\theta}}(t)) - \sigma_X^{k\perp}(t) \hat{\boldsymbol{\epsilon}}_X^{\perp}(t)|, \\ \sigma_X^{\perp}(t) &= \frac{1}{N} \sum_{k=1}^{N} |(\boldsymbol{\theta}^k(t) - \bar{\boldsymbol{\theta}}(t)) \cdot \hat{\boldsymbol{\epsilon}}_X^{\perp}(t)|, \end{cases} \quad (2)$$

where $\sigma_X^{k\perp}(t) = (\boldsymbol{\theta}^k(t) - \bar{\boldsymbol{\theta}}(t)) \cdot \hat{\boldsymbol{\epsilon}}_X^{\perp}(t)$ and N is the stride number.

When $\sigma_X^{\|}(t)$ is larger than $\sigma_X^{\perp}(t)$, such distribution of the joint angles suggests the existence of joint synergy that suppresses the deviation of the horizontal toe position $X(t)$ relative to the hip position. To judge the existence of the joint synergy, we used the degree of synergy $S(t)$ defined by

$$S(t) = \frac{\sigma^{\|}(t)}{\sigma^{\perp}(t)}. \quad (3)$$

By the definition, $S > 1$ indicates the existence of joint synergy.

In this study, we computed two kinds of the UCM components, $\sigma_X^{\|}$ and $\sigma_Y^{\|}$, for the UCMs on which the vertical and horizontal components of the toe position relative to the hip position are constant, respectively. Their orthogonal components, $\sigma_X^{\perp}$ and $\sigma_Y^{\perp}$, were also computed.

III. RESULTS AND DISCUSSION

In this section, we will explain the common characteristics of joint synergy observed in two macaque subjects by showing data of the subject KA.

A. Control of toe position

Fig. 4 and 5 show the results of the UCM analysis of the left and right leg movement during bipedal walking, respectively. The subfigures (a) and (b) show the results when the UCMs are set by the manifold on which the horizontal and vertical toe position relative to the hip position, X and Y, are constant, respectively. Thin lines show the components of the variance of the leg joint angles which do not change the horizontal and vertical toe position, $\sigma_X^{\|}$ and $\sigma_Y^{\|}$, the broken lines show the components of variance which affect the horizontal and vertical toe position, $\sigma_X^{\perp}$ and $\sigma_Y^{\perp}$, and the thick lines show the degree of joint synergy, S_X and S_Y,

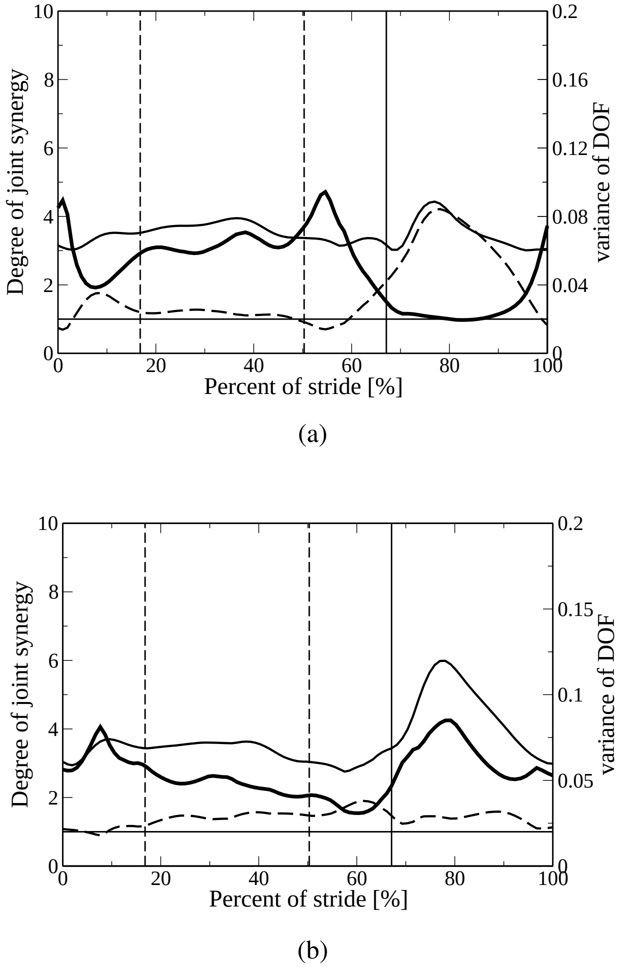

Fig. 4. The components of variance of the leg joint angles and the degree of joint synergy observed in the left leg trajectory of the macaque subject KA. (a) and (b) show results when UCMs are set by the plane on which the horizontal, X, and vertical, Y, toe position relative to the hip position are constant, respectively. The horizontal axis shows percent of stride time. 0% of the stride time is the start of stance phase, 66.5% (indicated by the vertical line) and 100% of the stride time show the start and the end of swing phase, respectively. Thin, broken and thick lines show $\sigma_X^{\parallel}$ and $\sigma_Y^{\parallel}$, $\sigma_X^{\perp}$ and $\sigma_Y^{\perp}$, and the degree of joint synergy S_X and S_Y, respectively.

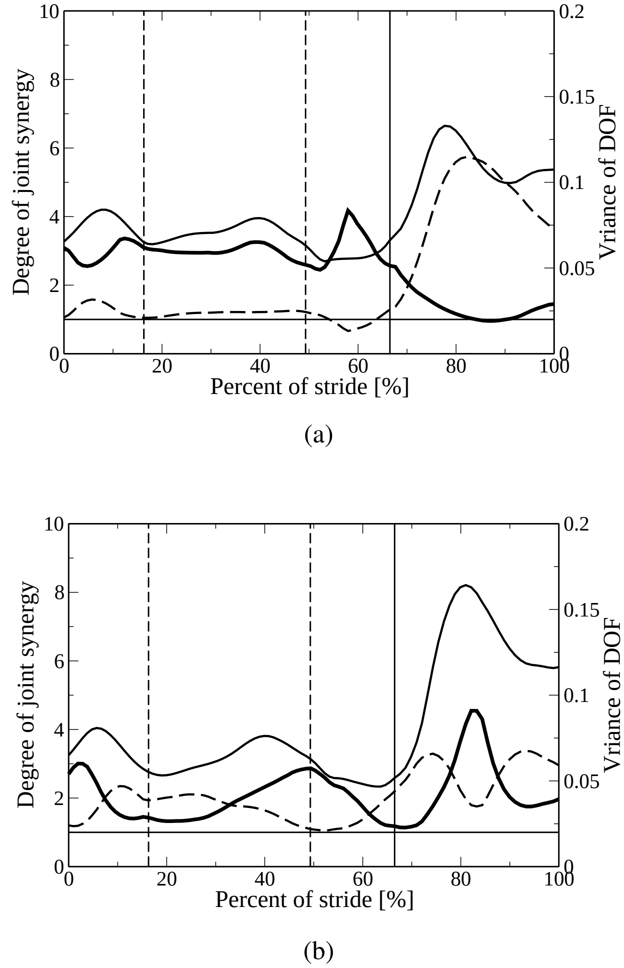

Fig. 5. The components of variance of the leg joint angles and the degree of joint synergy observed in the right leg trajectory of the macaque subject KA. The lines are the same as those in Fig. 4.

respectively. Fig. 6 and 7 show the temporal profile of the horizontal toe position, X, and the distance between hip and toe, respectively. We analyzed the stance and swing phase independently by normalizing each duration of obtained data. The ratio of the duration of the stance and swing phase shown in the figures is determined by the average of the ratio of measured data. The stride time 0%, 16.8$\pm$1.8 S.D.%, 50.5$\pm$1.5 S.D.%, and 67.1$\pm$1.5 S.D.% are the start of the stance phase (i.e. the first double support phase), single support phase, the second double support phase and swing phase, respectively, for the left leg, and 0%, 16.3$\pm$1.7 S.D.%, 49.3$\pm$1.9 S.D.%, and 66.5$\pm$2.8 S.D.% for the right leg.

Over the stance phase, S_X is larger than one (Fig. 4(a), 5(a)), which suggests that the variance of the horizontal toe position relative to the hip position is suppressed by joint synergy. In other words, the variance of the horizontal hip position is suppressed at the stance phase. During the second double support phase (around 55% of stride time) S_X takes large value, which suggests that the horizontal hip position is adjusted by joint synergy. Fig. 6 and 7 suggest that the leg is extended backward and the hip angle is close to its limit of the range of motion [2], [3] around the moment. These results might suggest that the large synergy S_X during double support phase be caused by the constraint given by musculoskeletal system. However, it would be also possible that the synergy is produced by control system in order to adjust the hip position by using two legs.

Over the entire stride period, S_Y is larger than one (Fig. 4(b), 5(b)), which suggests that the variance of the vertical toe position is suppressed by joint synergy. At the middle of swing phase (around 80% of stride time) when the leg is folded (Fig. 7) and the tip of the long finger passes its lowest position from the ground, S_Y takes the largest value which suggests that the variance of the vertical toe position becomes small and the toe height is precisely controlled by joint synergy, which would contribute to avoid accidental stumbling due to fluctuation of leg movement. Before touch down (90-100% of stride time), variances, e.g. $\sigma_X^{\parallel}$ and $\sigma_Y^{\parallel}$, stay large value, however, the joint synergies, S_X and S_Y, show increase (Fig. 4(a)(b), 5(a)(b)), which suggests that the variance of the toe position is suppressed by joint synergy

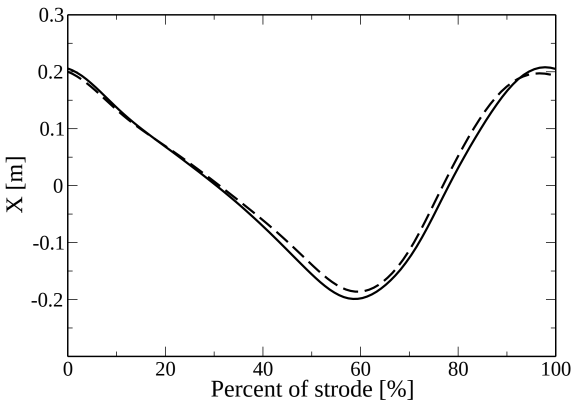

Fig. 6. The horizontal toe position during bipedal walking of a macaque. Solid and broken lines show the movements of the left and right leg, respectively.

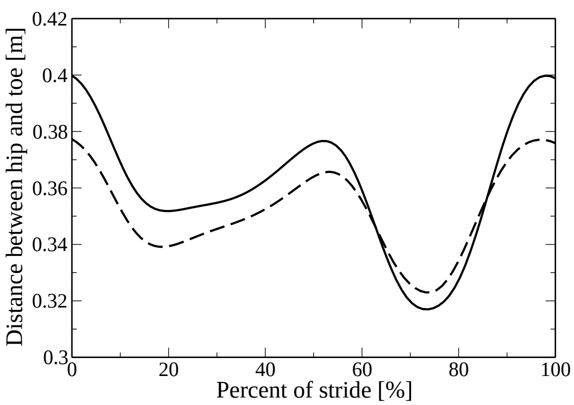

Fig. 7. The distance between hip and toe during bipedal walking of a macaque. Solid and broken lines show the movements of the left and right leg, respectively.

in preparation for touch down.

At the end of the second double support phase (60-66.5% of stride time), S_Y shows the minimum value in the left leg shown in Fig. 4(b), on the other hand, S_Y of the right leg takes a peak value (Fig. 5(b)). In fact, macaques walk by a posture such that their sagittal plane take diagonal from the direction of movement. These results suggest that the asymmetry of the walking pattern of macaques is due to different control scheme for two legs.

B. The differences of joint synergy in bipedal walking between macaques and humans

The following are the same characteristics observed in bipedal walking of humans and macaques. The variance of the vertical toe position is suppressed by joint synergy over the entire stride period [8]. When the tip of the finger passes its lowest position from the ground, the variance of the vertical toe position was suppressed by joint synergy [8], which would be an important strategy to avoid stumbling and realize stable walking.

On the other hand, some differences between humans and macaques were also found. Just before the touch down at the end of swing phase high joint synergy that suppresses the variance of the toe position was observed in macaque walking. However, in human walking, the degree of synergy was often smaller, instead, the variances of each joint angle was suppressed before touch down [8]. These results suggest that the foot position at grounding is controlled in both of macaques and humans, however, the control strategy would be different. Furthermore, high joint synergy that adjusts the hip height was observed at the second double support phase in human walking, on the other hand, the walking pattern of macaques was asymmetric and such joint synergy was found only in one leg of both macaque subjects. These results also indicate that there exists difference in control strategy between humans and macaques.

IV. Conclusion

We examined how and when the toe position relative to the hip position are controlled by the synergy between the hip, knee, and ankle joints during macaque bipedal walking. Our results have shown that the joint synergy especially works during double support phase and at the middle of swing phase when the tip of the finger passes the lowest position. These results suggest that joint synergy seems to be exploited at the moments when precise control is required to realize stable bipedal locomotion. On the other hand, some differences of the synergy pattern were found between human and macaque walking, e.g. at the end of swing phase joint synergy seems to be less utilized in human walking, instead the variance of joint angles are suppressed. These results indicate that different control strategy would be used in the bipedal locomotion of humans and macaques. However, our results do not exclude the possibility that some synergies observed in this study might be realized by physical constraints. To investigate this possibility is our future preblem.

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