35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

An analysis of leg joint synergy during backward walking

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***Abstract*— Grasso et al. (1998) proposed the hypothesis that motor commands for the backward walking is designed so as to reproduce the reversal motion of forward walking. In this study, we analyzed the leg joint synergy in backward walking by the UCM analysis and compared the results with the time reversal profile of the synergy in forward walking. Some similarities between them were observed, e.g., the body posture is controlled by utilizing joint synergy during double support phase. However, differences were also observed during swing phase, e.g., at touch down at the end of swing phase the joint synergy is utilized to adjust the foot position in backward walking, contrary in forward walking the synergy is not utilized but the variance of joint angles are suppressed. The results indicate that the backward walking is not a reversal motion of forward walking, but planned independently of forward walking.**

I. INTRODUCTION

Grasso et al. suggested that the motor commands for backward walking is planned so as to produce the reversal motion of forward walking [1], [2]. On the other hand, our previous study have suggested that the leg swing trajectories of forward and backward walking are designed so as to minimize the energy cost under some constraints that stabilizes walking [3]. Many other previous studies also have shown the evidences that legged locomotor patterns are well optimized on energy cost [4]–[9]. It might be possible that the backward walking is a reversal motion of the forward walking as Grasso et al. suggested, and the resultant backward walking is also optimal based on energy cost, however, the examination of the validity of the Grassos' hypothesis would be important to understand the mechanism of motor planning by our nervous system.

Recent our analysis has shown that the joint trajectories during walking show some fluctuations for each stride, however, such fluctuations are mutually compensated each other so as to suppress the fluctuation of the toe position at some specitic moments in a stride cycle, e.g., during double support phase and at the moment when stumbling often occurs in the middle of the swing phase [3]. Such cooperative joint movements are called joint synergy, and our analysis suggested that high joint synergy is often observed at critical points to realize stable walking. In this paper, we examine the validity of Grassos' hypothesis by analyzing the leg joint synergy in backward walking and comparing the results with the reversal time profile of the synergy in forward walking.

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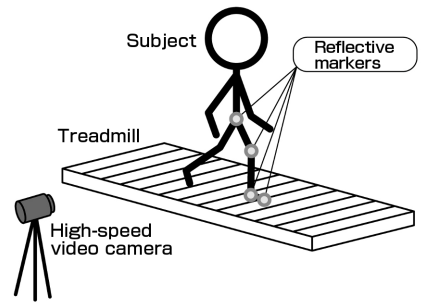


Fig. 1. The overview of the measurement of walking.

TABLE I
BODY PARAMETERS OF THE SUBJECTS. ALL SUBJECTS ARE MALE.

Subject	Age	Weight [kg]	Thigh [m]	Shank [m]	Foot [m]
A	21	56.4	0.403	0.395	0.119
B	23	63.4	0.419	0.428	0.128
C	19	60.0	0.406	0.425	0.137

II. METHODS

A. Measurement of walking

We measured the leg trajectories of subjects who equipped reflective marker at the hip, knee, ankle walked on a treadmill at 4.5 km/h (Fig. 1). The subjects were three males in their teens or twenties with no disorder in their lower extremities. They did not know the purpose of this study and gave their informed consent prior to the experiment. TABLE I shows their body parameters. The walking speed were not informed to the subjects during the experiment, and measurements were started without notifying them after some period to allow for adaption to walking treadmill. The trajectories were recorded by a motion capture system (Himawari SP200, LIBRARY Inc.) at 200 fps and smoothed by the 6th-order low-pass Butterworth filter with the cutoff frequency of 6 Hz. At the end of stance phase during backward walking, subjects kicked the ground with the heel or toe. However, since the latter is a rare, we analyzed only the former data.

B. The UCM analysis

Scholz and Schöner proposed the idea of Uncontrolled Manifold (UCM) analysis to quantitatively assess the synergy, a cooperative behavior, among several degrees of freedom (DOFs) [10]. The UCM is defined as a manifold that expresses the combination of control variables, e.g., joint angles, which can accomplish a given task. For instance, if the given task is to bring the toe height to a target height, the UCM is the manifold in the leg joint space on which the toe

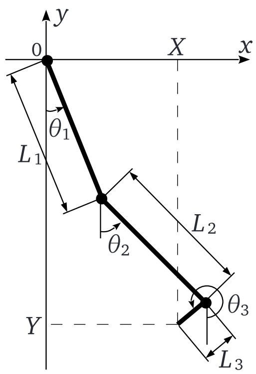


Fig. 2. Three-link leg model used in the UCM analysis. Each closed circle shows the hip, knee, and ankle joint in the order from the origin. Each leg joint angle θ_n $(n = 1,\ 2,\ 3)$ is defined as positive counter-clockwise with respect to the vertical axis. L_n $(n = 1,\ 2,\ 3)$ shows the thigh, shank, and foot length. The position $(X,\ Y)$ shows the toe position relative to the hip position.

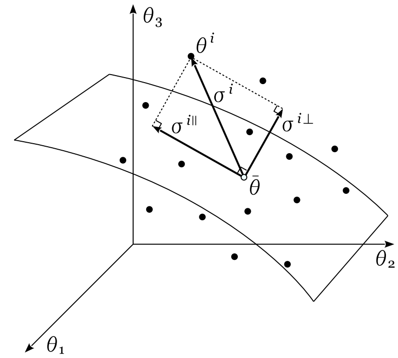


Fig. 3. Schematic view of the UCM analysis for joint synergy. The axes show joint angles, each closed circle shows the joint angle $\boldsymbol{\theta}^i$ at a specific stride time during walking, and the open circle shows the average $\bar{\boldsymbol{\theta}}$ of the joint angles. The curved surface is the schematic view of the UCM on which the toe height, e.g., $Y(\boldsymbol{\theta})$ is constant. The projective lines, $\boldsymbol{\sigma}^{i\|}$ and $\boldsymbol{\sigma}^{i\perp}$, show the parallel and orthogonal components of the deviation $\boldsymbol{\sigma}^i$ of a joint angle to the UCM, respectively. The former component of deviation dose not affect the toe height but the latter dose.

height is at the target value. Scholz and Schöner proposed that the variance of the control variables on the UCM is often allowed in movement tasks of living bodies and redundant number of control variables cooperatively work so as to obtain the solution on the UCM. In fact, recent studies have supported this hypothesis for various movement tasks [11]–[13].

In this study, we modeled the leg as a simple three-link system that moves in a sagittal plane (Fig. 2), and analyzed the leg movement during walking as follows. The leg trajectory data of 25 strides of each subject were divided into stance and swing phase and normalized by the duration of each phase, respectively. 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, $\bar{\theta}_j$ shows the averaged joint angle, and the subscript $j = 1,\ 2,$ and 3 represent the hip, knee, and ankle, respectively. The distribution of the deviation of the joint angles $\boldsymbol{\sigma}^i(t) = \boldsymbol{\theta}^i(t) - \bar{\boldsymbol{\theta}}(t)$ was analyzed by the UCM analysis, where $\boldsymbol{\theta}^i(t) = \left(\theta_1^i(t),\ \theta_2^i(t),\ \theta_3^i(t)\right)^T$ $(i = 1,\ 2,\ \cdots, N)$ is the joint trajectory of the i-th stride (Fig. 3), and $N = 25$ is the stride number. In the UCM analysis, we selected the joint angles as control variables and analyzed whether these control variables cooperatively work so as to adjust the vertical and horizontal toe position relative to the hip position. The analytical method is almost the same used in [14]. We summarize the method for the case when the UCM is set as the manifold in the joint angle space on which the toe height is the constant value $Y\left(\bar{\boldsymbol{\theta}}\right)$.

The toe height $Y(\boldsymbol{\theta})$ is given by the joint angles

$$Y(\boldsymbol{\theta}(t)) = L_1\cos(\theta_1(t)) + L_2\cos(\theta_2(t)) + L_3\cos(\theta_3(t)), \tag{1}$$

where L_k $(k = 1,\ 2,\ 3)$ shows the link lengths (Fig. 2). In this case, the UCM on which the toe height takes a constant value is two-dimensional in the joint angle space and $\boldsymbol{\varepsilon}_Y^{\perp}(t) = \nabla_{\boldsymbol{\theta}} Y\big|_{\boldsymbol{\theta}=\bar{\boldsymbol{\theta}}}$ shows the orthogonal direction to the UCM at $\boldsymbol{\theta} = \bar{\boldsymbol{\theta}}(t)$. The UCM component $\boldsymbol{\sigma}_Y^{i\|}(t)$ of the deviation of the i-th stride $\boldsymbol{\sigma}_Y^i(t)$ and its orthogonal component $\boldsymbol{\sigma}_Y^{i\perp}(t)$ are given by

$$\begin{cases} \boldsymbol{\sigma}_Y^{i\|}(t) = \boldsymbol{\sigma}^i(t) - \boldsymbol{\sigma}_Y^{i\perp}(t) \\ \boldsymbol{\sigma}_Y^{i\perp}(t) = \left(\hat{\boldsymbol{\varepsilon}}_Y^{\perp}(t)\cdot\boldsymbol{\sigma}^i(t)\right)\hat{\boldsymbol{\varepsilon}}_Y^{\perp}(t), \end{cases} \tag{2}$$

where $\hat{\boldsymbol{\varepsilon}}_Y^{\perp}(t) = \boldsymbol{\varepsilon}_Y^{\perp}(t) / \left|\boldsymbol{\varepsilon}_Y^{\perp}(t)\right|$. We define here two kinds of variances, one is the UCM component of the variance $\sigma_Y^{\|2}(t)$ and the other is its orthogonal component $\sigma_Y^{\perp 2}(t)$ given by

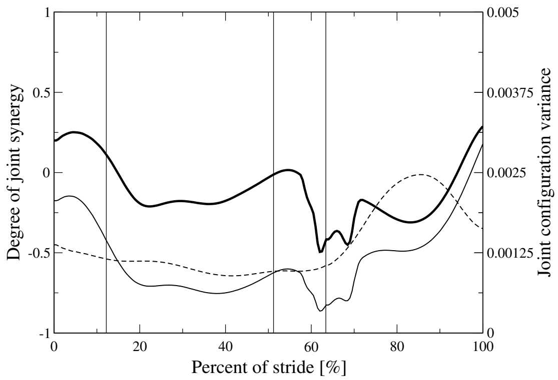
$$\begin{cases} \sigma_Y^{\|2}(t) = \dfrac{1}{n-d}\cdot\dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\left|\boldsymbol{\sigma}_Y^{i\|}(t)\right|^2 \\ \sigma_Y^{\perp 2}(t) = \dfrac{1}{d}\cdot\dfrac{1}{N}\displaystyle\sum_{i=1}^{N}\left|\boldsymbol{\sigma}_Y^{i\perp}(t)\right|^2, \end{cases} \tag{3}$$

respectively, where n and d show the number of dimensions of the joint angle space and the orthogonal space to the UCM, respectively. When $\sigma_Y^{\|}(t)$ is larger than $\sigma_Y^{\perp}(t)$, such a distribution of the joint angles suggests the existence of joint synergy that suppresses the deviation of the toe height. To judge the existence of joint synergy, we defined the degree of synergy S_Y by

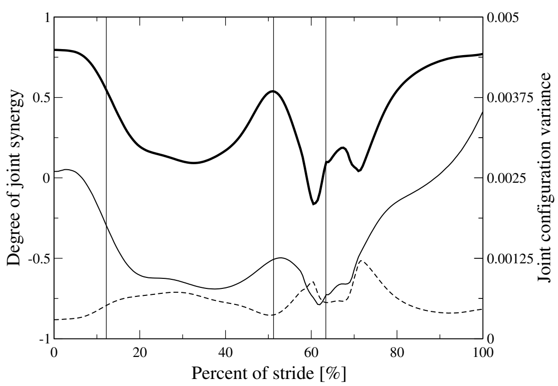
$$S_Y(t) = \frac{\sigma_Y^{\|2}(t) - \sigma_Y^{\perp 2}(t)}{\sigma_Y^{\|2}(t) + \sigma_Y^{\perp 2}(t)}. \tag{4}$$

By the definition $S_Y > 0$ indicates the existence of joint synergy, i.e., the variance of the vertical toe position effectively suppressed by the joint synergy.

In this study, we computed two kinds of UCM components, $\sigma_X^{\|2}(t)$ and $\sigma_Y^{\|2}(t)$, for the UCMs on which the horizontal and vertical components of the toe position are constant, respectively. Their orthogonal components, $\sigma_X^{\perp 2}(t)$ and $\sigma_Y^{\perp 2}(t)$, and the degree of synergy, S_X and S_Y, were also computed.

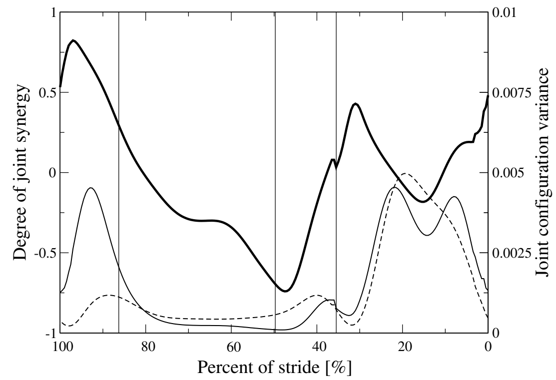


(a)

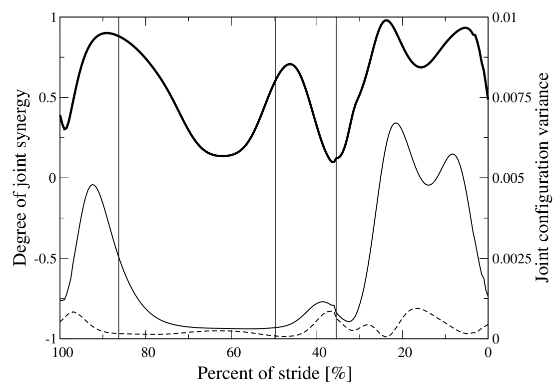


(b)

Fig. 4. The degree of synergy and the components of the variance of the leg joint angles during backward walking at 4.5 km/h of the subject A. The subfigures (a) and (b) show the results when the UCMs are set as the manifold on which the horizontal and the vertical toe position relative to the hip position, X and Y, are constant, respectively. The horizontal axis shows the percent of the stride time, the time 0% shows the start of the stance phase, i.e. the first double support phase, and the time 100% shows the end of the swing phase. The vertical lines show the start of the single support phase, the second double support phase, and the swing phase from the left to the right. The thin lines show the UCM components of the variances, $\sigma_X^{\parallel 2}$ and $\sigma_Y^{\parallel 2}$, the broken lines show their orthogonal components, $\sigma_X^{\perp 2}$ and $\sigma_Y^{\perp 2}$, and the thick lines show the degrees of synergy, S_X and S_Y, respectively.



(a)



(b)

Fig. 5. The degree of synergy and the components of the variance of the leg joint angles during forward walking at 4.5 km/h of the subject A. The subfigures (a) and (b) show the results when the UCMs are set as the manifold on which the horizontal and the vertical toe position relative to the hip position, X and Y, are constant, respectively. Note that the horizontal axis is reversal of Fig. 4, i.e., the time 0% shows the start of the swing phase, and the time 100% shows the end of the stance phase. Note that the vertical axis is reversely displayed in order to make it easy to compare reversal of the forward walking shown in this figure with backward waking (Fig. 4). The vertical lines show the start of the stance phase, i.e., the first double support phase, the single support phase and the second double support phase from the right to the left. The others are the same as those in Fig. 4.

III. RESULTS AND DISCUSSION

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

Fig. 4 and 5 show the results of the UCM analysis of leg joint trajectories of the subject A during backward and forward walking at 4.5 km/h, respectively. The subfigures (a) and (b) show the results when the UCMs are set as the manifold on which the horizontal and vertical toe position relative to the hip position, X and Y, are constant, respectively. The horizontal axis shows the percent of the stride time, and in Fig. 4 the time 0% shows the start of the stance phase (i.e. the first double support phase), and the time 100% shows the end of the swing phase. the time 13.71±1.63 S.D.%, 50.28±1.10 S.D.%, and 64.52±1.42 S.D.% are the start of the single support phase, the second double support phase, and the swing phase, respectively. In Fig. 5 the horizontal axis is reversely shown in order to make it easier to compare the reversal motion of forward walking with the backward walking, i.e., the time 0% shows the start of the swing phase, and the time 100% shows the end of the stance phase; the time 35.48±1.42 S.D.%, 49.72±1.10 S.D.%, and 86.29±1.63 S.D.% are the start of the stance phase (i.e. the first double support phase), the single support phase, and the second double support phase, respectively.

The first double support phase in backward walking (around 0%–10% of stride time) corresponds to the second double support phase in the reversal motion of forward walking (around 90%–100% of stride time). In both cases S_X and S_Y take a local maximum value, which suggests that the variance of the hip position relative to the toe position is effectively suppressed by the joint synergy, which would contribute to suppress the fluctuation of the trunk position and to realize stable walking.

On the other hand, S_Y in forward walking takes a local maximum value at the middle of the swing phase (around 23% of the stride time in Fig. 5(b)), at the moment the toe passes its lowest position from the ground. This result suggests that the joint synergy works strongly at the critical moment to suppress the risk of stumbling as reported in [15]. However, there is no such peak of S_Y in backward walking at the corresponding moment (around 77% of the stride time in Fig. 4(b)). This would reflect the difference in the foot trajectory: in backward walking the foot gradually approaches to the ground during swing phase, on the other hand in forward walking the foot height often takes the lowest height in the middle of swing and then raised up again.

At the end of the swing phase, S_Y takes high value in backward walking (around 90–100% of the stride time in Fig. 4(b)), i.e., the variance of the toe height is effectively suppressed by the joint synergy at touch down. On the other hand, at the touch down in forward walking (35% of the stride time in Fig. 5(a)(b)) all variances, $\sigma_X^{\parallel 2}$, $\sigma_X^{\perp 2}$, $\sigma_Y^{\parallel 2}$, and $\sigma_Y^{\perp 2}$, take low values, and S_X and S_Y are small, therefore, the variances of the leg joint angles are effectively suppressed without utilizing joint synergy. It has been also reported that in biped walking of Japanese macaques the variance of the toe position at touch down is suppressed by joint synergy [12]. These results suggest that the strategy of touch down might have changed through evolution and learning from the strategy that utilizes joint synergy to another one that precisely adjusts joint angles without utilizing synergy.

IV. CONCLUSION

In this study, we analyzed the leg joint synergy in backward walking by the UCM analysis and examined how hip, knee, and ankle joints cooperate so as to suppress the variances of the toe position relative to the hip position. Some similarities were observed between the time profile of the joint synergy in backward walking and the time reversal profile of the synergy in forward walking, however, differences were also observed during swing phase especially at the moment of touch down. These results suggest that the control scheme for backward walking is not to realize a reversal motion of forward walking and seems to be designed independently.

As mentioned in Introduction, it has been suggested the leg swing trajectories are optimized based on the energetic cost in forward and backward walking and many studies have shown that legged locomotor patterns are optimized on energy cost. Therefore, it would be possible that backward walking is also designed so as to suppress the energetic cost under some different control strategy from forward walking that contributes to stabilize backward walking.

ACKNOWLEDGMENT

This work was partially supported by KAKENHI (22500526 and 25282183).

REFERENCES

[1] R. Grasso, L. Bianchi, and F. Lacquaniti. Motor patterns for human gait: Backward versus forward locomotion. *Journal of Neurophysiology*, Vol. 80, No. 4, pp. 1868–1885, 1998.

[2] R. Grasso, Y. P. Ivanenko, M. Zago, M. Molinari, G. Scivoletto, and F. Lacquaniti. Recovery of forward stepping in spinal cord injured patients does not transfer to untrained backward stepping. *Experimental Brain Research*, Vol. 157, No. 3, pp. 377–382, 2004.

[3] J. Nishii, Y. Hashizume, S. Kaichida, H. Suenaga, and Y. Tanaka. Constraint and exploitation of redundant degrees of freedom during walking. *Robotics and Autonomous Systems*, Vol. 60, No. 5, pp. 679–684, 2012.

[4] M. Y. Zarrugh, F. N. Todd, and H. J. Ralston. Optimization of energy expenditure during level walking. *European Journal of Applied Physiology and Occupational Physiology*, Vol. 33, No. 4, pp. 293–306, 1974.

[5] M. Y. Zarrugh and C. W. Radcliffe. Predicting metabolic cost of level walking. *European Journal of Applied Physiology and Occupational Physiology*, Vol. 38, No. 3, pp. 215–223, 1978.

[6] A. E. Minetti and R. M. Alexander. A theory of metabolic costs for bipedal gaits. *Journal of theoretical biology*, Vol. 186, No. 4, pp. 467–476, 1997.

[7] J. Nishii. Legged insects select the optimal locomotor pattern based on the energetic cost. *Biological cybernetics*, Vol. 83, No. 5, pp. 435–442, 2000.

[8] J. M. Donelan, R. Kram, and A. D. Kuo. Mechanical and metabolic determinants of the preferred step width in human walking. *Proceedings of The Royal Society Lond. B*, Vol. 268, No. 1480, pp. 1985–1992, 2001.

[9] J. Nishii. An analytical estimation of the energy cost for legged locomotion. *Journal of theoretical biology*, Vol. 238, No. 3, pp. 636–645, 2006.

[10] J. P. Scholz and G. Schöner. The uncontrolled manifold concept: identifying control variables for a functional task. *Experimental Brain Research*, Vol. 126, No. 3, pp. 289–306, 1999.

[11] M. L. Latash, J. P. Scholz, and G. Schöner. Motor control strategies revealed in the structure of motor variability. *Exercise and sport sciences reviews*, Vol. 30, No. 1, pp. 26–31, 2002.

[12] S. Kaichida, Y. Hashizume, N. Ogihara, and J. Nishii. An analysis of leg joint synergy during bipedal walking in Japanese macaques. *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE*, pp. 8183–8186, 2011.

[13] Y. H. Wu, V. M. Zatsiorsky, and M. L. Latash. Multi-digit coordination during lifting a horizontally oriented object: synergies control with referent configurations. *Experimental Brain Research*, Vol. 222, No. 3, pp. 277–290, 2012.

[14] M. L. Latash, J. P. Scholz, and G. Schöner. Toward a new theory of motor synergies. *Motor control*, Vol. 11, No. 3, pp. 276–308, 2007.

[15] S. Kaichida, Y. Hashizume, and J. Nishii. An analysis of leg trajectories of human walking from the view point of joint coordination. *Proceedings of the 3rd International Symposium on Mobiligence*, pp. 409–412, 2009.