Contribution of each joint to the inter-joint synergy during walking

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1 Introduction

In human walking, the joint trajectories are not the same at each step and show some variability. Such variability can affect the minimum toe clearance (MTC), which may result in stumbling; however, the variability of the toe height at the moment of the MTC is suppressed by joint synergy among the hip, knee, and ankle joints [1]. In this study, we evaluated how leg joints contribute to the formation of the joint synergy by using the uncontrolled manifold (UCM) analysis [2] and covariation by randomization (CR) analysis [3].

2 Methods

2.1 Data Acquisition

Eight healthy subjects in their twentieth (6 males and 2 females) participated in this study. The study was approved by the Institutional Review Board of Yamaguchi University Hospital and written consent was obtained from the participants prior to participation. Kinematic data were measured using a motion capture system (Himawari SP200, Library Co., Ltd.; sampling rate 200 Hz). Reflective markers were placed at the greater trochanter (hip), knee, lateral malleolus (ankle), and the fifth metatarsal head (toe) on the left side of the body. Participants walked on a treadmill by 4.5 km/h with crossing their arms across their chest in order not to hide the reflective markers from the motion capture system. The kinematic data were bidirectionally low-pass filtered at 6 Hz with a sixth-order Butterworth filter. $N = 30$ stride data were extracted and divided into the stance and swing phases. The duration of the stance and swing phase were adjusted to each average durations, united as one stride, and then divided into 100 time steps.

2.2 Data Analysis

The joint synergy among hip, knee, and ankle joints that suppresses the variability of the toe height Y relative to the hip height was examined at each time step in a stride period by the UCM and CR analyses.

The procedure of the CR analysis used in this study was as follows. Let the joint angle of the k-th stride ($k = 1,\dots,N$) and the mean angle $\boldsymbol{\theta}_k(t)$ and $\overline{\boldsymbol{\theta}}(t)$, respectively. The deviation of the joint angle $\boldsymbol{\sigma}_k(t)$ from the mean angle was computed, i.e., $\boldsymbol{\sigma}_k(t) = \boldsymbol{\theta}_k(t) - \overline{\boldsymbol{\theta}}(t)$, for each subject. By permutating the deviation of each joint angle, surrogate deviation data $\boldsymbol{\sigma}_i^*(t)$ ($i = 1,\dots,N^3$) and surrogate joint angle data $\boldsymbol{\theta}_i^*(t) = \overline{\boldsymbol{\theta}}(t) + \boldsymbol{\sigma}_i^*(t)$ were generated. The degree of joint synergy R_Y was defined by

$$R_Y = 1 - \frac{V_{emp}}{V_0}, \tag{1}$$

where V_{emp} and V_0 are the variances of the empirically measured toe height and estimated toe height from the surrogate data in which all covariations among joints were removed. Positive R_Y means the existence of the covariation among the joints that suppresses the variability of the toe height.

The procedure of the UCM analysis was as follows [1]. The variance of the joint angles of $N = 30$ strides was decomposed into the orthogonal (ORT) component ($\sigma_Y^{\perp 2}(t)$) that affects the toe height and the UCM component ($\sigma_Y^{\parallel 2}(t)$) that does not. The degree of joint synergy is defined by

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

Positive S_Y means the existence of joint synergy that suppresses the variability of the toe height. The UCM analysis judges that the joint synergy exists not only when covariation between joints exists but also when the variance of a specific joint angle is large but its effect on the toe height is small [4]. This is because the UCM analysis is based on Bernstein's hypothesis that "variations that do not affect task evaluation are acceptable" [5].

3 Results and Discussion

3.1 Joint synergy at each phase during walking

Figure 1 and 2 show the joint synergies that suppress the variance of the toe height evaluated by the UCM and CR analyses, respectively. Although subjects walked on a treadmill with crossing their arms because of restriction of our measurement environment, no significant difference was observed in the joint synergy from the previous study analyzing free walking by the UCM analysis [6]. At the beginning of the second double support phase and the moment of the MTC, both of the degrees of joint synergies evaluated by the UCM and CR analyses take the maximum values, suggesting that joint covariation suppresses the variability of the toe height relative to the hip height at these moments.

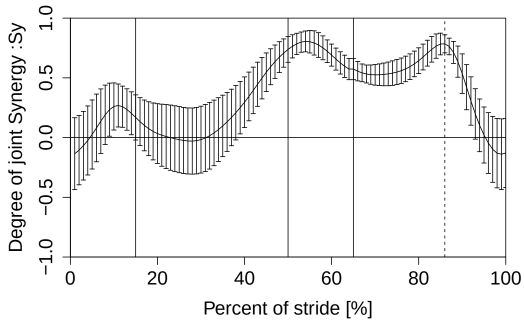

Figure 1: The inter-subject mean±SD of the degree of joint synergy that stabilizes the toe height evaluated by the UCM analysis. The abscissa shows the percent of the stride time: the origin and vertical solid lines show the start of the stance phase, single support phase, second double support phase, and swing phase, respectively, from the left to the right. The vertical broken line shows the moment of the MTC.

From the latter half of the second double support phase to the start of the swing phase, the value of R_Y becomes smaller and takes a negative value. Therefore, no covariation among leg joints is observed in this period. Contrary, S_Y remains large, suggesting the existence of the joint synergy under the definition by the UCM analysis. In this period, the foot direction is almost vertical to push off the ground, hence the effect of variability of the ankle joint angle on the hip height is small, in other words, the variability of the ankle angle is allowed during the push-off phase.

3.2 Contribution of each joint angle to joint synergy

To evaluate the contribution of the hip, knee, and ankle joints to the formation of the joint synergy that suppresses the variability of the toe height, the CR analysis was performed by permuting the deviation of a specific joint angle (Fig. 3). The degrees of the joint synergies evaluated by permuting only the knee or ankle data were almost the same as the result obtained by permuting all joint data (Fig. 2), whereas the degree of the synergy evaluated by permuting only the hip joint data was lower. This result suggests that the joint synergy that suppresses the variance of the toe height in the second double support phase and at the MTC is due to the covariation between the knee and ankle joints and that the contribution of the hip joint to the synergy is low.

4 Conclusions

In this study, joint synergy during walking was analyzed by the UCM and CR analyses. The results showed that the covariation between the knee and ankle joints was mainly involved in the formation of joint synergy to adjust the toe height, but the contribution of the hip joint was small. Hence, the main role of the hip joint might be to swing a leg and the knee and ankle joints cooperatively work so as to improve walking stability by adjusting toe height relative to the hip height.

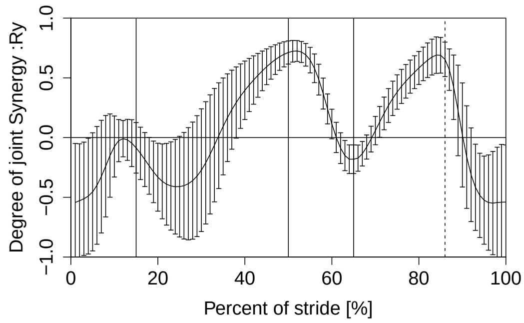

Figure 2: The inter-subject mean±SD of the degree of joint synergy that stabilizes the toe height evaluated by the CR analysis. The vertical lines show the same as those in Fig.1.

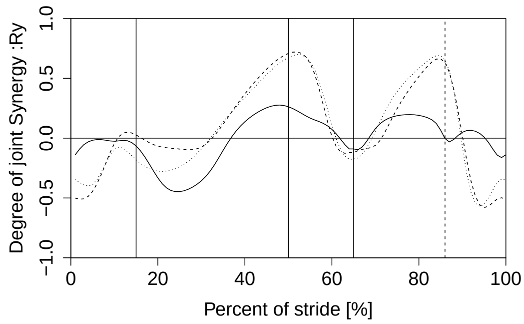

Figure 3: The inter-subject means of degrees of joint synergies that stabilize the toe height evaluated by the CR analysis with permuting each joint data. The solid, dotted, and broken lines show the results when only the hip, knee, and ankle joints were randomized, respectively. The vertical lines show the same as those in Fig.1.

5 Acknowledgments

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