A CPG-based Control of Bipedal Locomotion by Exploiting Deformable Feet

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Abstract: In this paper, we investigate adaptive bipedal walking that exploits sensory information stemming from a "soft deformable" body. To this end, we modeled soft deformable feet for a bipedal robot and a CPG-based control of bipedal locomotion that exploits local sensory feedback generated from the deformation of these feet. Through numerical simulations, we have found that a bipedal robot controlled by the proposed controller exhibits remarkably adaptive walking in response to experimental perturbations. This result supports the conclusion that the "deformation" of a robot's body plays a pivotal role in the emergence of "sensor-motor coordination", which is the key to generating adaptive locomotion in a robotic system.

Keywords: Deformable feet, CPG, Adaptive bipedal walking

1. INTRODUCTION

Animals exhibit astoundingly adaptive, supple and versatile locomotion under real world constraints by orchestrating large degrees of bodily freedom. Recent studies have clarified that this amazing capability is controlled in part by an intraspinal neural network called *central pattern generators* (CPGs) [1].

Based on this biological finding, various studies have been conducted so far to incorporate artificial CPGs into legged robots with the aim of generating highly adaptive locomotion [2], [3]. A key concept underlying these studies is to generate a limit cycle in the state space, which is composed of brain-nervous system (*i.e.*, control system), musculoskeletal system (*i.e.*, mechanical system) and environment. Once a limit cycle is established, its intrinsic structural stability allows the robot to exhibit resilience against environmental perturbations. However, the design principle that can assuredly establish a limit cycle with a large basin of attraction have not yet been devised.

This paper aims to generate a more stable limit cycle by exploiting the spatiotemporal sensory information stemming from the *deformability* of a robot's body, leading to a close interaction between motion and perception (*i.e.*, sensor-motor coordination [4]), which will in turn accomplish adaptive locomotion. To this end, we give attention to the deformability of soft human feet during bipedal walking. A soft body enables a robot to not only stabilize its motion but also gain *rich* sensory information, which stems from the deformation in ways favorable to the motion underway. In this paper, we propose a novel CPG-based control method for bipedal locomotion, in which local sensory information stemming from the deformability is fed back to a coupled oscillator system. Simulation results indicate that the proposed model enhances the adaptability in response to environmental perturbations by exploiting the sensory information stemming from soft deformable feet. We expect these findings to prove the useful in the development of a methodology that allows robots to generate adaptive locomotion.

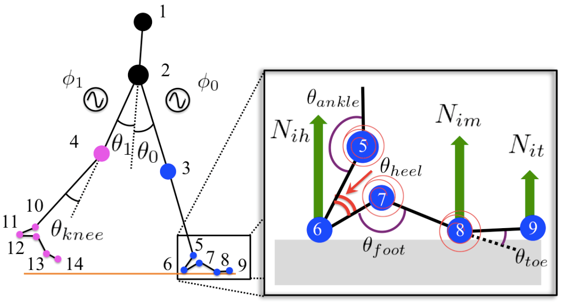


Fig. 1 Schematic representation of musculoskeletal system.

2. MODEL

Figure 1 shows the musculoskeletal system employed in this study. The model we adopted was inspired by the deformation of human feet during walking [5]. The closeup in this figure shows the skeletal system of the feet in detail. Here, the key point of the present model is that the torsion springs are purposefully put into the joints: ankle, foot, and toe. Because such elastic materials can deform in ways favorable to the motion underway, the deformation of the feet provides rich information about how the robot interacts with the environment as well as stabilizing motion (*e.g.*, shock absorption). In this paper, we model a control scheme for a bipedal robot by using local feedback of the sensory information stemming from these deformable feet. The actuators at the hip joints drive the legs back and forth using PD (proportional and differential) control such that the hip angles $\theta_i (i = 0, 1)$ correspond to the target angles $\theta_{di} (i = 0, 1)$. We implemented a stopper into the knee joint, which prevents hyperextension.

The phase oscillators described in (1) are implemented for the hip joints in our model:

$$\dot{\phi}_i = \omega + \epsilon \sin(\phi_j - \phi_i - \pi) + f_i, \qquad (1)$$

where ω represents the intrinsic frequency of the ith oscillator (left: $i = 0$, right: $i = 1$). The second term on the right hand side denotes the interaction between the

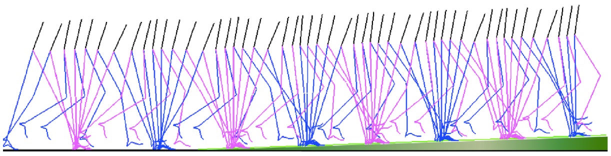


Fig. 2 Stick diagram showing environmental change from level ground to sloping ground (2.0 deg.) during 9 periods.

oscillators. ϵ represents the magnitude of the interaction. The third term denotes the local sensory feedback from the musculoskeletal system to this control system. In this paper, we model the local sensory feedback as follows:

$$f_i = (aN_{ih} + bN_{im} + cN_{it})\cos\phi_i. \tag{2}$$

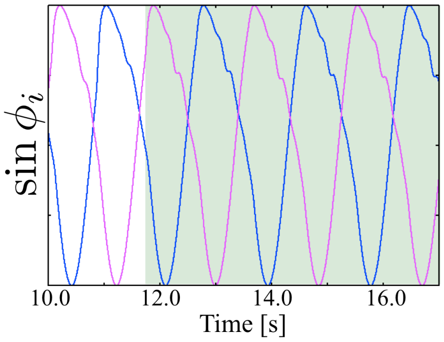
As shown in Fig. 1, N_{ih}, N_{im}, and N_{it} represent GRFs (ground reaction forces) perpendicular to the ground at the heel (6 and 11), metatarsal (8 and 13), and toe (9 and 14), respectively. The parameters a, b, and c represent the magnitudes of the sensitivities to these GRFs. These parameters play a crucial role in modulating the phases based on the sensory information from the superficial senses (N_{ih}, N_{im}, N_{it}).

3. SIMULATION RESULT

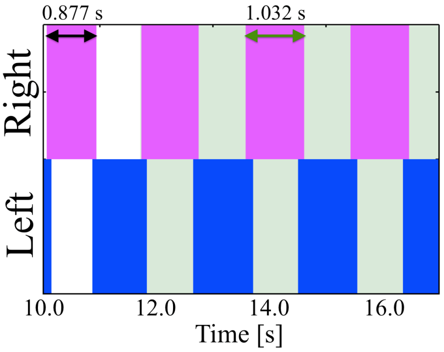
We show the simulation results in terms of the adaptability in response to environmental changes. Here, we set the control parameters in our model as follows: $\omega = 4.4$ rad/s, $\epsilon = 0.30$, $a = 0.011$, $b = 0.008$, $c = 0.008$, $C_1 = 0.384$ rad, and $C_2 = 0.454$ rad. Fig. 2 shows a stick diagram of the transition from walking on level ground to walking on sloping ground (2.0 deg). As this figure shows, the proposed model generates a phase modification based on the situation encountered. This result indicates that the local sensory feedback stemming from the sensory information of the deformable feet allows the spontaneous modification of the step length during walking, leading to the convergence to steady-walking on sloping ground. Fig. 3 shows the oscillator phases, $\sin\phi_i$, and gait diagram used in the verification. In these figures, the light green area represents the walking on the sloping ground. As this figure shows, the period of the stance phase is spontaneously modified from 0.877 s (level ground) to 1.032 s (sloping ground) by the local sensory feedback in response to the environment.

4. SUMMARY

In this study, we proposed a control scheme that exploits the local sensory feedback stemming from deformable soft feet. Simulation results indicate that the proposed model enhances the adaptability in response to environmental perturbations. The key in our model is the exploitation of a reasonable degree of physical deformation in soft feet, reflecting the interaction between the robot and environment. In future, we will discuss the detailed model of the musculoskeletal system in human feet, which deform in ways favorable to the motion underway. And we aim to develop a real bipedal robot to further verify the validity of this design scheme.



(a)



(b)

Fig. 3 Simulation results for transition during environmental change from level ground to sloping ground (2.0 deg) (10.0–17.0 s): (a) oscillator phases and (b) gait diagram.

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