Soft Deformable Feet Yield Sensory-motor Coordination for Adaptive Bipedal Walking

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1 Introduction

Animals exhibit astoundingly adaptive, supple, and versatile locomotion under real world constraints. This amazing ability is achieved via close interaction between the brain-nervous system, the musculoskeletal system, and the environment [1]. *Sensory-motor coordination* [2], *i.e.*, the induction of sensory stimulation through movement, and in turn, the influence of sensory stimulation on the movements, plays an essential role in generating these interaction dynamics, leading to the realization of locomotion.

Here, we present an adaptive bipedal walking robot based on sensory-motor coordination induced by soft deformable feet. In this work, we focus on soft deformable feet that directly interact with the environment and gain sensory information via bipedal walking. We hypothesize that 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 related to the current motion.

Most researchers have investigated the effect of the foot function on the dynamical stability of bipedal walking. McGeer *et al.* and some other researchers discussed the arc-shaped foot effect in the context of passive dynamics [3, 4]. In the field of biomechanics, Hansen *et al.* showed that *roll-over shapes*, *i.e.*, center of pressure (CoP) trajectories in the shank coordinates, do not significantly change with walking speed; this contributes to walking stability similar to that of passive dynamic walkers [5]. Adamczyk *et al.* investigated the effect of arc foot radius on the mechanical and metabolic costs of walking [6]. Narioka *et al.* demonstrated that a robot exhibits stable walking by exploiting the roll-over shape configured by the elasticity of the ankle joint [7]. However, very few researchers have discussed the foot function from the viewpoint of gaining rich sensory information or in the context of sensory-motor coordination.

In this work, we develop a bipedal walking robot with soft deformable feet, and we propose a *central pattern generator* (CPG)-based control scheme that exploits local force feedback generated from the deformation of these feet. We verify the validity of the proposed controller experimentally by deploying the constructed bipedal robot in real-world conditions. We find that the robot controlled by the proposed controller exhibits remarkably stable walking by exploiting the deformability of these feet.

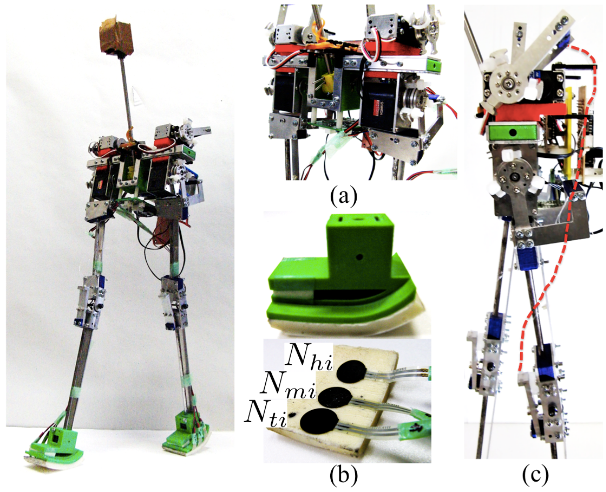

Figure 1: Constructed bipedal robot: (a) waist section, (b) soft foot, and (c) knee reflex mechanism.

2 Biped robot with soft feet

Figure 1 shows the complete structure of the constructed bipedal robot. It consists of two legs, an upper body segment, and a waist section. The total weight of the robot is approximately 1.6 kg. The lengths of the legs and upper body segment are 0.40 and 0.20 m, respectively. For simplicity, we conducted walking experiments by constraining the motion in the sagittal plane (similar to two-dimensional walking).

Figure 1 (a) shows the detailed structure of the waist section. As shown in the figure, this section is equipped with two servomotors (Kondo Kagaku Co., Ltd.; KRS-4014S) that drive the legs using proportional-derivative (PD) control. A potentiometer (Alps Electric Co., Ltd.; RDC506002A) detects the angle between the upper body segment and the waist section, which is used for the standard position of the target angles for PD control. The upper body is attached to this section via a joint with an elastic element. Each leg has a passive knee joint (Fig. 1 (c)) and is equipped with a soft foot (Fig. 1 (b)). As shown in Fig. 1 (c), to prevent the robot from falling over, we implement a reflex mechanism at the knee joint, which locks the knee angle using a servomotor (Kondo Kagaku Co., Ltd.; KRS-2350HV) and a elastic wire (like fishline) when the foot contacts the ground. The robot has two microprocessors (AVR ATmega 328P and 648P) for controlling the knee reflex mechanism and computing the oscillator phases in the legs. The servomotor at the hip joint drives the legs according to the phase of the corresponding oscillator.

Figure 1 (b) shows the detailed structure of the soft feet. The soles of feet are equipped with soft silicone gel (EXSEAL Corporation; human skin gel, Asker-C 15) whose texture is similar to that of human skin. To detect the ground reaction forces (GRFs), we attached three pressure sensors (Interlink Electronics Inc.; FSR402) to the intermediate section between the sole and the silicone gel (Fig. 1 (b)). Because such elastic materials can deform in ways related to the current motion, the deformation of the feet provides versatile sensory information regarding the robot's interaction with its environment.

Coupled phase oscillators described are implemented for the generation of rhythmic leg movement of robot, and they are expressed as

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

where ω denotes the intrinsic angular velocity of the ith oscillator (left $i = 0$, right $i = 1$). The second term on the right-hand side denotes the interaction between the oscillators, such that these phases converge to anti-phase synchronization. In addition, ε denotes the magnitude of interaction between the oscillators. The third term denotes the local sensory feedback sent from the force sensors of the feet to this coupled oscillator system (control system). In this paper, we model the local force feedback as

$$f_i = (aN_{hi} + bN_{mi} + cN_{ti}) \cos \phi_i. \tag{2}$$

where N_{hi}, N_{mi}, and N_{ti} denote the GRFs detected by the pressure sensors in each foot, as shown in Fig. 1 (b). Parameters a, b, and c denote the magnitudes of the sensitivity to these GRFs.

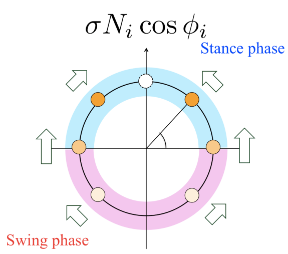

Figure 2: Schematic of oscillator dynamics depending on local sensory feedback $\sigma N_i \cos \phi_i$.

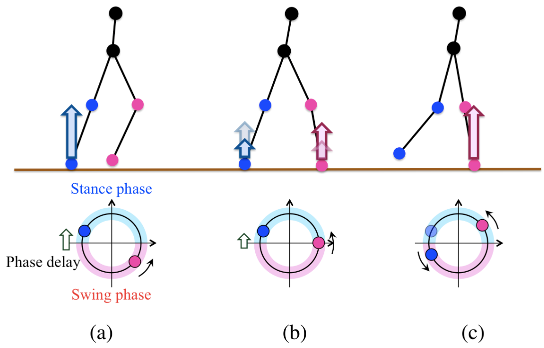

Figure 3: Schematic showing the physical effect of local sensory feedback. The pink and blue points in the lower part of the figure denote the phases ϕ_i of the right and left legs oscillator, respectively.

The target angle θ_{di} of the PD controller given by phase ϕ_i of the oscillators is expressed as

$$\theta_{di} = C_{amp} \cos \phi_i + C_{off}, \tag{3}$$

where C_{amp} and C_{off} denote the amplitude and offset angle of the target angle θ_{di} in the leg swing, respectively. Each target angle of the PD control corresponds to the desired angle between the leg and the upper body.

Next, we explain the mechanism of the phase modulation in detail; this mechanism exploits the local force feedback. The legs are controlled by the PD controller such that the ith leg supports the body on the ground (*stance phase*) for $0 \le \phi_i < \pi$ and lifts off the ground (*swing phase*) for $\pi \le \phi_i < 2\pi$, as shown in Fig. 2. For simplicity, we explain phase modulation (2) for a case in which the feet have a single mass point (Fig. 3) as

$$f_i = \sigma N_i \cos \phi_i, \tag{4}$$

where N_i and ϕ_i denote the GRF and oscillator phase of the corresponding leg, respectively, and σ denotes a positive constant describing the magnitude of the sensory feedback. The oscillator phase is mainly modulated to tend to be $\pi/2$ during the stance phase when $N_i > 0$, owing to the influence of local sensory feedback (Fig. 2). For example, if a leg continues to bear a load ($N_i > 0$) at the end of its stance phase ($\phi_i \approx \pi$), a phase delay is introduced, as shown in Fig. 3 (a), to prevent the robot from falling over. This phase delay, which is introduced when $f_i < 0$, allows sufficient time for the other leg to enter the stance phase (Fig. 3 (b)). As the other leg begins to support the body, the load on the corresponding leg decreases; consequently, the feedback effect decreases, allowing it to enter the swing phase (Fig. 3 (c)). Therefore, the local sensory feedback, which allows the legs to maintain the stance phase by exploiting the local force sensory information from the feet, governs the appropriate relationship between the phases in the coupled oscillators and the leg movements. In the detailed foot structures

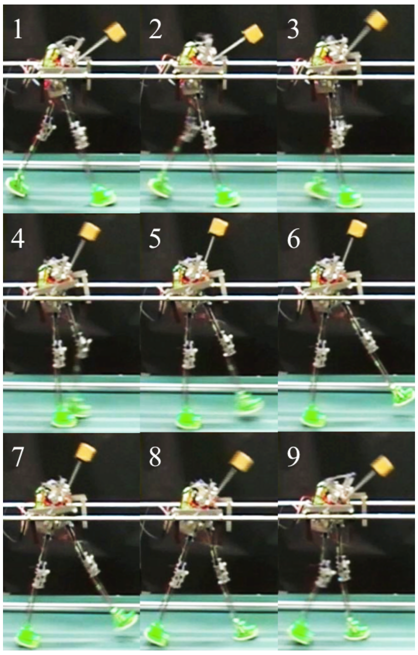

Figure 4: Photographs taken during steady walking at 0.10 s intervals.

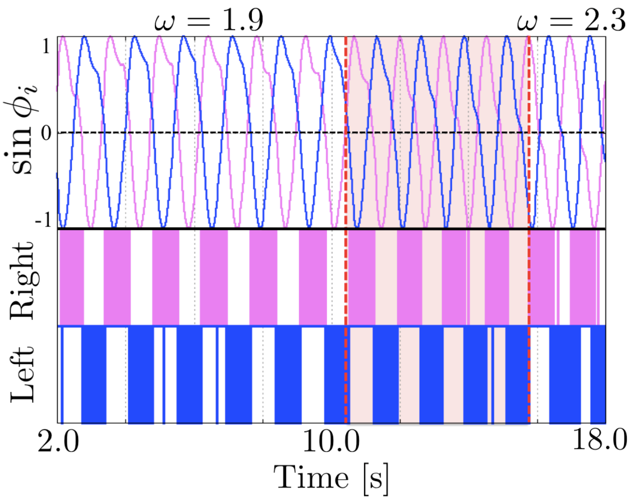

Figure 5: Experimental results of transition during a change in walking velocity by changing ω.

shown in Fig. 1 (b), the local sensory feedback based on the sensory information (N_{hi}, N_{mi}, N_{ti}), as described by (2), enables phase modulation based on a reasonable degree of physical deformation, reflecting the interaction between the robot and its environment and leading to the generation of adaptive behavior.

3 Experimental results

Here, we set the control parameters of our robot by trial and error as follows: $\omega = 1.9$ rad/s, $\varepsilon = 0.1$, $a = 0.010, b = 0.008, c = 0.006$, $C_{amp} = 0.384$ rad, and $C_{off} = 0.174$ rad. Fig. 4 shows photographs of steady walking motion captured every 0.10 s. As shown in this figure, we achieved steady walking motion by exploiting the local sensory feedback stemming from the deformation of the soft feet.

Figure 5 shows the experimental results of changing ω (ω is changed from 1.9 to 2.3 rad/s at t = 10.7 to 15.7 s). These results indicate that our robot exhibits good adaptability to a change in walking velocity ω. Note that the amount of phase modification significantly changes before and after a velocity change. Moreover, we confirmed that the duty factor of each leg, which is defined by the stance period of one foot as a percentage of the gait cycle, changes autonomously in response to a velocity change.

4 Open questions

From these results, we conclude that the deformation of a robot's body plays a pivotal role in the emergence of sensory-motor coordination, which is crucial to the generation of adaptive locomotion in robotic systems. The open questions are summarized as: (1) what role does the deformability of soft feet play in the emergence of adaptive walking?, and (2) how should the generation of rich sensory information and stabilization of motion be reconciled by exploiting the deformability?

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