"TEGOTAE"-Based Control of Bipedal Walking

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Abstract. Despite the appealing concept of "central pattern generator" (CPG)-based control for bipedal walking, there is currently no systematic methodology for designing a CPG controller. To tackle this problem, we employ a unique approach: We attempt to design local controllers in the CPG model for bipedal walking based on the viewpoint of "TEGOTAE", which is a Japanese concept describing how well a perceived reaction matches an expectation. To this end, we introduce a TEGOTAE function that quantitatively measures TEGOTAE. Using this function, we can design decentralized controllers in a systematic manner. We designed a two-dimensional bipedal walking model using TEGOTAE functions and constructed simulations using the model to verify the validity of the proposed design scheme. We found that our model can stably walk on flat terrain.

Keywords: Bipedal walking · TEGOTAE · Plantar sensation · Central pattern generator (CPG)

1 Introduction

Humans and animals exhibit astoundingly adaptive and versatile locomotion given real-world constraints. To endow robots with similar capabilities, their bodies must have a significantly larger number of degrees of freedom than what they have at present. To successfully coordinate movement with many degrees of freedom in response to various circumstances, "autonomous decentralized control" plays a pivotal role and has therefore attracted considerable attention.

In fact, animals deftly coordinate the many degrees of freedom of their bodies using distributed neural networks called "central pattern generators" (CPGs), which are responsible for generating rhythmic movements, particularly locomotion [1,2]. Based on these biological findings, various studies have been conducted thus far to incorporate artificial CPGs into legged robots with the aim of generating highly adaptive locomotion [3–6]. However, there is currently no systematic methodology for designing a CPG controller; each individual CPG model has been designed on a completely ad hoc basis for a specific practical situation.

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To tackle this issue, we herein introduce a unique approach: We attempt to design local controllers using the CPG model for bipedal walking based on the viewpoint of "TEGOTAE", which is a Japanese concept describing how well a perceived reaction, i.e., sensory information, matches an expectation, i.e., an intended motor command. To this end, we introduce the TEGOTAE function, which quantitatively measures TEGOTAE. This function can be described as the product of "what a local controller wants to do" and "its resulting reaction" on the basis of the concept of TEGOTAE. Thus, by only designing local sensory feedback such that each local controller increases "consistent" TEGOTAE in line with "expectation," or decreases "inconsistent" TEGOTAE otherwise, we can design decentralized controllers in a systematic manner. In this paper, we proposed a systematic design scheme of a decentralized CPG controller for bipedal walking based on TEGOTAE and verify the validity of the scheme through simulation.

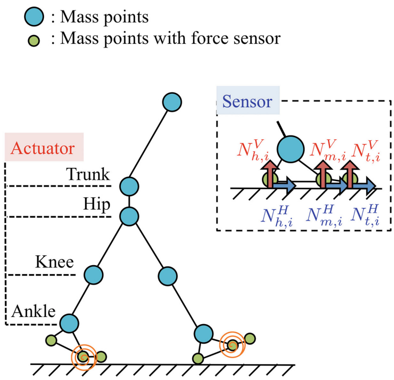


Fig. 1. Bipedal walking model.

2 Bipedal Walking Model

2.1 Musculoskeletal Structure

To validate the design scheme based on the TEGOTAE function, we conducted simulations using a two-dimensional bipedal walking model. Figure 1 shows the musculoskeletal structure of the bipedal walking model, whose movements are constrained in the sagittal plane for simplicity. We implemented seven actuators on the waist joint, two hip joints, two knee joints, and two ankle joints, at which each actuator generates torque based on proportional-derivative (PD) control, as explained in Sect. 2.2. Passive springs and dampers are implemented into the toe joints to passively generate an effective push-off force at the end of the stance phase. On the basis of findings in humans and animals, which have shown that cutaneous receptors in the foot play an essential role in the control of gait [7–9], we modeled plantar sensations that can detect vertical and horizontal ground reaction forces (GRFs) ($N^V_{x,i}$ and $N^H_{x,i}$) to the ground at heel ($x = h$), metatarsal ($x = m$), and toe ($x = t$) points on the feet. Here, the suffix i denotes each leg ($i = 0$: right and $i = 1$: left).

2.2 Systematic Design Scheme of a CPG Controller Based on the "TEGOTAE" Function

The proposed control system for bipedal walking consists of four components: (1) hip controllers, (2) knee controllers, (3) ankle controllers, and (4) a posture controller. The first three components coordinate the inter- and intra-limb movements via TEGOTAE functions for adaptive walking, and the forth component stabilizes the upper body using the waist actuator and vestibular sensor. Due to space limitations, the details of the posture control are not presented here.

Hip, knee, ankle, and waist joint torque $\tau_{y,i}$ in the i^{th} leg (y indicates one of the joints) are generated by the PD control using the following equations:

$$\tau_{hip,i} = -K_{hip,i}(\theta_{hip,i} - \bar{\theta}_{hip,i}) - D_{hip,i}\dot{\theta}_{hip,i}, \tag{1}$$

$$\tau_{knee,i} = -K_{knee,i}(\theta_{knee,i} - \bar{\theta}_{knee,i}) - D_{knee,i}\dot{\theta}_{knee,i}, \tag{2}$$

$$\tau_{ankle,i} = -K_{ankle,i}(\theta_{ankle,i} - \bar{\theta}_{ankle,i}) - D_{ankle,i}\dot{\theta}_{ankle,i}, \tag{3}$$

$$\tau_{trunk} = -K_{trunk}(\theta_{trunk} - \bar{\theta}_{trunk}) - D_{trunk}\dot{\theta}_{trunk}, \tag{4}$$

where $\theta_{y,i}$ and $\bar{\theta}_{y,i}$ are the actual and target angles at joint y in the i^{th} leg, respectively. Furthermore, $K_{y,i}$ and $D_{y,i}$ are the proportional and derivative gains of the PD controller at joint y. Hip, knee, and ankle controllers can modulate the target angles $\bar{\theta}_{y,i}$ and the proportional gains $K_{y,i}$ using the TEGOTAE function to generate adaptive walking.

The TEGOTAE function is a function formulated using the concept of TEGOTAE, which is described as the product of the (i) intended motor command of a controller $f(x)$, where x denotes a control variable, and (ii) resulting sensory information $g(\boldsymbol{S})$ obtained from sensor values $\boldsymbol{S}$ as follows:

$$T(x, \boldsymbol{S}) = f(x)g(\boldsymbol{S}), \tag{5}$$

where we design the TEGOTAE function such that it increases if we gain sensory information that is consistent with the intended motor command. Positive/negative values of the TEGOTAE function indicate consistency/inconsistency between the intended motor command and resulting sensory information.

Using TEGOTAE function $T(x, \boldsymbol{S})$, we can modulate the local control variable x as follows:

$$\dot{x} = h(x) + \frac{\partial T(x, \boldsymbol{S})}{\partial x}, \tag{6}$$

where the first term on the right denotes the intrinsic dynamics of the local controller, and the second term denotes the local sensory feedback for variable x

based on the TEGOTAE function. Using the sensory feedback described by the partial differential form of the TEGOTAE function, the controller modulates its control variable x such that it increases consistent TEGOTAE with expectation, or decreases inconsistent TEGOTAE otherwise. We now describe the local joint controllers at the hip, knee, and ankle joints designed using the TEGOTAE functions.

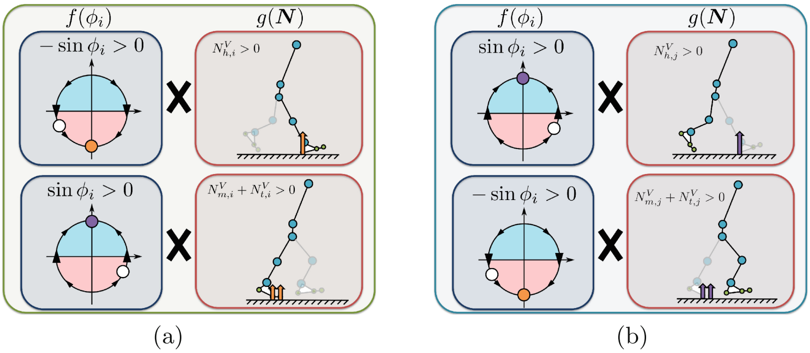


Fig. 2. Definition of the TEGOTAE function for the hip controller. (a) TEGOTAE function based on the corresponding leg's sensory information. (b) TEGOTAE function based on the other leg's sensory information.

Hip Control. The role of the hip joints in human waking is rhythmic motion generation for forward and backward leg swing [10]. To generate such rhythmic movements, we use phase oscillators to generate the target angle of the hip actuators (Eq. 1), which are described by the following equation:

$$\bar{\theta}_{hip,i} = -C_{1,hip}\cos\phi_i + C_{2,hip}, \tag{7}$$

where $C_{1,hip}$ and $C_{2,hip}$ [rad] denote the amplitude and offset angles of the hip target angle, respectively. According to the oscillator phases ϕ_i, legs are controlled to be in the swing phase for $0 \leq \phi_i < \pi$ and in the stance phase for $\pi \leq \phi_i < 2\pi$.

The dynamics of the phase oscillators with the local sensory feedback using the TEGOTAE function are as follows:

$$\dot{\phi}_i = \omega + \frac{\partial T_{hip,i}(\phi_i, \boldsymbol{N})}{\partial \phi_i}, \tag{8}$$

where ω [rad/s] denotes the intrinsic angular velocity of the oscillators. The TEGOTAE function for the hip control is defined as the following equation:

$$\begin{aligned} T_{hip,i}(\phi_i, \boldsymbol{N}) = \;& \sigma_{hip,1}\{N^V_{h,i}(-\sin\phi_i) + (N^V_{m,i} + N^V_{t,i})(\sin\phi_i)\} \\ &+ \sigma_{hip,2}\{N^V_{h,j}(\sin\phi_i) + (N^V_{m,j} + N^V_{t,j})(-\sin\phi_i)\}, \end{aligned} \tag{9}$$

where $\sigma_{hip,1}$ and $\sigma_{hip,2}$ [rad/Ns] denote the feedback gains. The suffix i and j denotes the corresponding and other legs, respectively. The first term on the right represents the TEGOTAE function based on the sensory information of the corresponding leg (Fig. 2(a)). The value of $N^V_{h,i}(-\sin\phi_i)$ becomes a positive value when the heel sensor on the corresponding leg detects a large vertical GRF ($N^V_{h,i} > 0$) and the oscillator phase is in the stance phase ($\pi < \phi_i < 2\pi$). By increasing this TEGOTAE term, the leg remains in the stance phase while supporting the body ($N^V_{h,i} > 0$). In contrast, the value of $(N^V_{m,i} + N^V_{t,i})$ $(\sin\phi_i)$ becomes positive value when the metatarsal and toe sensors on the corresponding leg detect a large vertical GRF ($N^V_{m,i} + N^V_{t,i} > 0$) and the oscillator phase is the swing phase ($0 < \phi_i < \pi$). In this case, by increasing this TEGOTAE term, the leg enters the swing phase at the end of stance phase ($N^V_{m,i} + N^V_{t,i} > 0$), which in turn pushes the body forward effectively. The second term represents the TEGOTAE function based on the sensory information of the other leg (Fig. 2(b)). The details of these effects are not explained here due to space limitation. By using the TEGOTAE-based local feedback in Eq. (8), the hip controllers enable "interlimb" coordination without any neural communication.

Knee Control. The role of a knee joint in human walking [10] is to support the body by increasing its stiffness in the stance phase and effective flexion by decreasing its stiffness in the swing phase. Thus, we define control variable χ_i, which denotes the control command that increases and decreases the stiffness of the knee joints. To implement such a stiffness control mechanism, we modify gain P in the knee controllers using χ_i as follows:

$$\tau_{knee,i} = -K_{knee,i}\theta_{knee,i} - D_{knee}\dot{\theta}_{knee,i}, \tag{10}$$

$$K_{knee,i} = \max[C_{1,knee}\tanh\chi_i, 0] + C_{2,knee}, \tag{11}$$

where $C_{1,knee}$ and $C_{2,knee}$ [Nm/rad] denote the variable range and offset value of gain P, respectively. In Eq. (10), the target angle $\bar{\theta}_{knee}$ of the knee controllers are set to 0 [rad], which indicates the state of the knee extension, allowing high/low stiffness to extend/flex the knee joints.

The dynamics of control variable χ_i with the local sensory feedback using the TEGOTAE function is as follows:

$$\dot{\chi}_i = -c_{knee,i}\chi_i + \frac{\partial T_{knee,i}(\chi_i, \boldsymbol{N})}{\partial \chi_i}, \tag{12}$$

where $c_{knee,i}$ denotes the time constant of the first order lag. The TEGOTAE function on the knee control is defined by the following equation:

$$T_{knee,i}(\chi_i, \boldsymbol{N}) = \sigma_{knee,1}N^V_i\chi_i + \sigma_{knee,2}N^V_j(-\chi_i), \tag{13}$$

where N^V_i and N^V_j [N] denote the sum of the vertical force sensor values on the heel, metatarsal, and toe, describing by, e.g., $N^V_i = N^V_{h,i} + N^V_{m,i} + N^V_{t,i}$, of the corresponding and other legs, respectively. Parameters $\sigma_{knee,1}$ and $\sigma_{knee,2}$ [1/N] denote the feedback gains. The first term on the right represents the TEGOTAE function based on the sensory information of the corresponding leg (Fig. 3(a) top). The value of $N_i^V \chi_i$ becomes a positive value when the foot sensors on the corresponding leg detect a large vertical GRF ($N_i^V > 0$) and the control command for the knee is increasing the stiffness ($\chi_i > 0$). Hence, by increasing this TEGOTAE term, the knee stiffness remains high while supporting the body ($N_i^V > 0$). The second term represents the TEGOTAE function based on the sensory information of the other leg (Fig. 3(a) bottom). Due to space limitation, the details of the effect is not explained here.

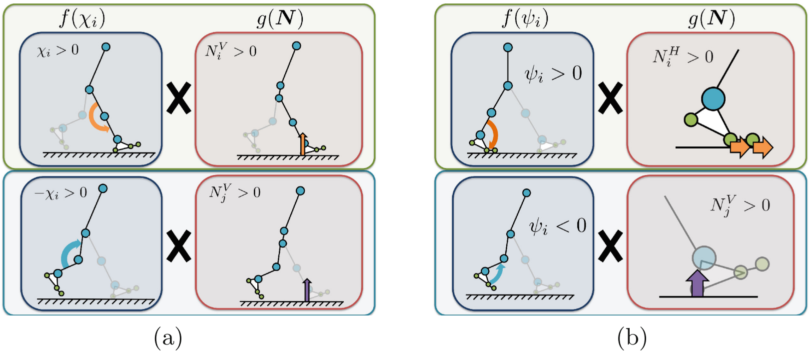


Fig. 3. Definition of the TEGOTAE function for the (a) knee and (b) ankle controller. Top: TEGOTAE function based on the corresponding leg's sensory information. Bottom: TEGOTAE function based on the other leg's sensory information.

Ankle Control. The role of an ankle joint in human walking [10] is to produce the push-off to generate the propulsion forces near the end of the stance phase and avoid colliding the foot with the ground during the swing phase. Thus, we define control variable ψ_i, which denotes the control command that increases or decreases the target angle of the ankle joints. We modify the target angle of the ankle controllers using ψ_i as follows:

$$\bar{\theta}_{ankle,i} = C_{1,ankle} \tanh \psi_i + C_{2,ankle}, \tag{14}$$

where $C_{1,ankle}$ and $C_{2,ankle}$ [rad] denote the variable range and offset value of the ankle target angle, respectively. The positive/negative value of ψ_i represents the plantar/dorsal flexion of an ankle joint.

The dynamics of control variable ψ_i with the local sensory feedback using the TEGOTAE function is as follows:

$$\dot{\psi}_i = -c_{ankle,i}\psi_i + \frac{\partial T_{ankle,i}(\psi_i, \boldsymbol{N})}{\partial \psi_i}, \tag{15}$$

where $c_{ankle,i}$ denotes the time constant of the first order lag. The TEGOTAE function on the ankle control is defined as follows:

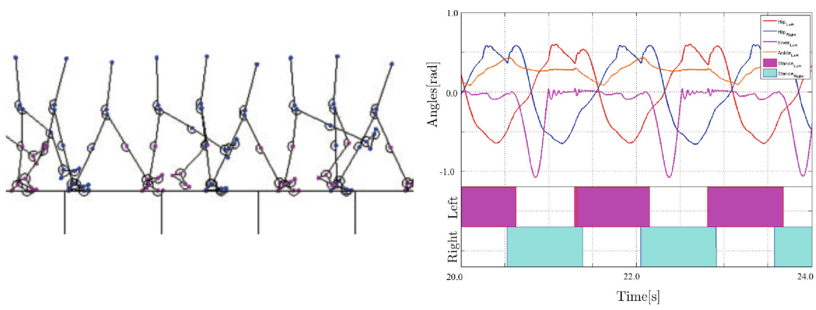
$$T_{ankle,i}(\psi_i, \boldsymbol{N}) = \sigma_{ankle,1} N_i^H \psi_i + \sigma_{ankle,2} N_j^V (-\psi_i), \tag{16}$$

where N_i^H [N] denotes the sum of the horizontal force sensor values on the heel, metatarsal, and toe of the corresponding leg, described by $N_i^H = N_{h,i}^H + N_{m,i}^H + N_{t,i}^H$. In addition, N_j^V [N] denotes the sum of the vertical force sensor values of the other leg, described by $N_j^V = N_{h,j}^V + N_{m,j}^V + N_{t,j}^V$. Parameters $\sigma_{ankle,1}$ and $\sigma_{ankle,2}$ [1/N] denote the feedback gains. The first term on the right represents the TEGOTAE function based on the sensory information of the corresponding leg (Fig. 3(b) top). The value of $N_i^H \psi_i$ becomes a positive value when the foot sensors on the corresponding leg detects a large horizontal GRF ($N_i^H > 0$) and the command for the ankle is plantar flexion ($\psi_i > 0$). Increasing this TEGOTAE term results in more effectively generating plantar flexion at the end of stance phase ($N_i^H > 0$), which in turn generates a larger propulsion force. The second term represents the TEGOTAE function based on the sensory information of the other leg (Fig. 3(b) bottom). Due to space limitation, the details of the effect is not explained here.

In sum, the advantage of our design scheme using the TEGOTAE functions is that we can systematically design controllers for many components by only designing TEGOTAE functions for each controllers; We simply have to design the appropriate TEGOTAE functions responsible for the target movements. Further, we expect that the TEGOTAE-based hip, knee, and ankle controllers enable spontaneous and adaptive "inter"- and "intra"-limb coordination via TEGOTAE functions.

3 Simulation Result

Here, we describe the verification of our proposed design scheme using numerical simulation. Figure 4 shows a stick diagram plot (a) and time series data (b) (both hip angles, left knee and ankle angles, and stance phases of both legs) of steady walking motion. As shown in this figure, we achieved steady walking motion by designing each joint controller based on the TEGOTAE functions. Note that the time series data of the simulation were similar to human data of walking [10].



(a) (b)

Fig. 4. Stick diagram (a) and time series data (b) of steady walking obtained over five periods. (Color figure online)

4 Conclusion and Future Work

The purpose of this study was to verify the validity of the proposed design scheme based on the TEGOTAE concept for bipedal walking. To this end, we constructed a bipedal walking model and applied our scheme to design joint controllers. We confirmed that the joint controllers designed using the TEGOTAE functions achieved stable bipedal walking on flat ground via spontaneous inter- and intra-limb coordination. The advantages of the proposed method over previous works [3,5] and the adaptability to environmental changes, which we did not verify, will be studied in future.

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