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Energy-Efficient Speed Control in a Reflex-based Bipedal Walking Model

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1 Introduction

Reflex circuits are neural circuits that generate basic locomotory motor patterns. They produce motor patterns automatically or involuntarily in response to sensory feedback. Previous studies found that reflex-based control is sufficient for generating bipedal gaits in musculoskeletal models [1]. Moreover, the generated gaits exhibited similarities in terms of muscle activity, joint angles, and torque patterns, compared to human locomotion [1, 2].

However, reflex-driven systems are limited by the difficulty to regulate speed, which requires a vast number of parameters to be properly tuned to achieve the target speed. Owing to the difficulty, there is limited information on the underlying mechanisms of reflex circuit modulation [3]. Thus, by reproducing speed control in a reflex-based control framework through simulations, we can gain further insights into reflex modulation mechanisms in bipedal walking.

In this study, we extend the reflex-based control system proposed in a previous study [1] to that with energy-efficient speed control. Hence, we propose the performance-weighted least-squares (PWLS) method, which is a polynomial regression technique capable of finding an approximate function by weighting parameters according to performance, e.g., energy efficiency. Using PWLS, we optimize the functions of control parameter values in the reflex circuits by incrementally increasing the input, i.e., target speed. Our results reveal that PLWS succeeded in finding a function of reflex-based model parameters for speed control and maintaining energy efficiency.

2 Walking Generation through Reflex-based Control

In this study, a two-dimensional (2D) musculoskeletal model was employed, as depicted in Figure 1. The basic structure is based on previous studies [1, 2]. The model represents a 180-centimeters-tall person weighing 80 kg. Each leg has eight muscle actuators modeling the gluteal muscle (GLU), hip flexor muscle (HFL), vasti (VAS), tibialis anterior (TA), soleus (SOL), hamstring (HAM), rectus femoris (RF), and gastrocnemius (GAS).

Our reflex-based control framework is modeled by the controller introduced by Geyer [1] and Wang [2]. The controller generates inputs for muscle stimulation using sensory feedback with a time delay.

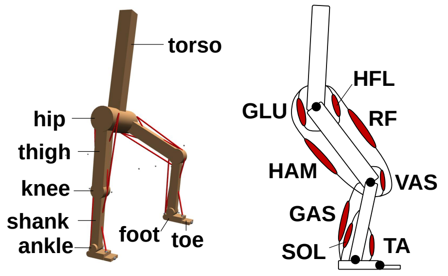

Figure 1: Structure of the musculoskeletal model.

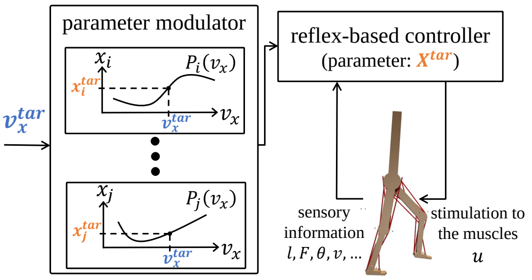

Figure 2: Control diagram for the musculoskeletal model.

3 Modulation of Control Parameters

Figure 2 illustrates the control diagram for the musculoskeletal model. The musculoskeletal model receives stimulation signals from the reflex-based controller, the parameters of which are represented by $\boldsymbol{X}^{tar}$. Each control parameter $x_i^{tar} \in \boldsymbol{X}^{tar}$ is calculated by continuous function $P_i(v_x)$ for input target velocity v_x^{tar}. We derived $P_i(v_x)$ by the polynomial regression of the relationship between velocity and the parameter value.

The data set for the polynomial regression was collected using optimization by incrementally increasing the target velocity. To generate an energy-efficient gait that follows the target speed, objective cost function f was designed as follows:

$$f(\boldsymbol{X}) = \sum_{t=1}^{T} r(\boldsymbol{s}_t) + \alpha_E \mathrm{CoT}, \tag{1}$$

where, $\boldsymbol{s}_t$ represents the state of the model at timestep t, r represents the reward function for state $\boldsymbol{s}_t$, α represents the

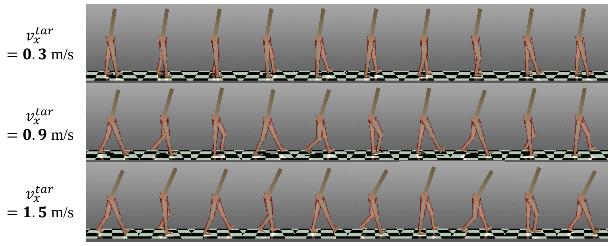

Figure 3: Snapshots of the generated gaits for $v_x^{tar} = 0.3, 0.9, \text{and} 1.2\,\mathrm{m/s}$ captured every $0.25\,\mathrm{s}$

weight coefficient, and CoT represents the cost of transport. r includes $r_{forward}$, which is defined as

$$r_{forward} = \alpha_v |v_x - v_x^{tar}|^2, \tag{2}$$

where, v_x represents the horizontal velocity of the model and v_x^{tar} represents the target velocity. The optimization begins with the target velocity v_x^{tar} set to v_{xmin}^{tar}. The target velocity is incrementally increased until it reaches the upper limit v_{xmax}^{tar}. If the model's gait is maintained to the upper timestep of the evaluation trial with control parameters $\boldsymbol{X}$, a tuple comprising the walking speed, control parameters, and CoT $\{(v_x, \boldsymbol{X}, \mathrm{CoT})\}$ is added to the data set.

Coefficients of P_i are calculated using PWLS. PWLS uses a polynomial regression algorithm that minimizes the total squared performance-weighted error of the collected data set $\{(v_{x1}, \boldsymbol{X}_1, \mathrm{CoT}_1), \ldots, \ldots (v_{xn}, \boldsymbol{X}_n, \mathrm{CoT}_n)\}$. The total squared performance-weighted error E_{PWLS} is defined as

$$E_{PWLS} = |\boldsymbol{\beta} \otimes (\boldsymbol{x}_i - \boldsymbol{V}\boldsymbol{\omega}_i)|^2, \tag{3}$$

where, $\boldsymbol{\beta} = [\beta_1, \ldots, \beta_j, \ldots, \beta_n]^{\mathrm{T}} \in \mathbb{R}^n$ represents the evaluated performance value of the corresponding data point j, $\boldsymbol{x}_i \in \boldsymbol{X}$ denotes the value of each control parameter, $\boldsymbol{V}$ denotes the observed velocities, $\boldsymbol{\omega}$ denotes the coefficients of P_i, and $\otimes$ denotes Hadamard product. In this study, we evaluated the performance of each data point in terms of energy efficiency through the CoT and designed β_i such that it takes on a higher value when CoT is low.

4 Simulation Results

Figure 3 displays snapshots of the generated steady walking for $v_x^{tar} = 0.3$, 0.9, and 1.5. The model adapted its behavior in response to v_x^{tar}. Figure 4 illustrates the model's speed when v_x^{tar}, depicted as a dotted line, was changed from 0.9 to 0.4 m/s, then to 0.7 m/s, and finally, to 1.2 m/s. As illustrated in the figure, the model regulates its speed with respect to the target velocity. Figure 5 exhibits the estimated cost of transport (CoT) curves for generated walking. Compared to the normal least square (LS) method, our proposed PWLS method produced a gait with lower CoT values. This result indicated that the PLWS found functions of energy-efficient parameters in the reflex-based model over various speeds.

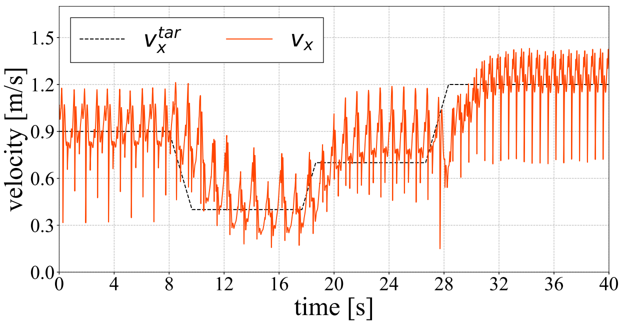

Figure 4: Time evolution of the generated walking speed (orange) in response to the target velocity v_x^{tar} (dotted line).

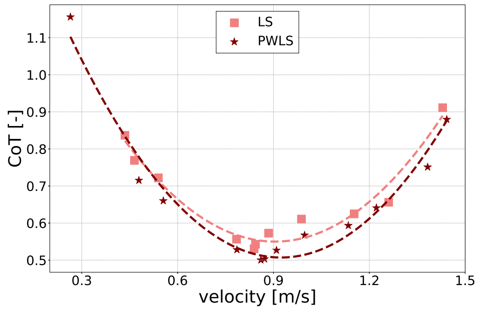

Figure 5: Estimated CoT curves for gaits generated through the normal least square (LS) method and PWLS method.

5 Conclusion

Reflex circuits generate basic locomotory patterns, and the modulation of their parameters enables the change in locomotion speed. In this study, we propose a method of adding energy-efficient speed control to the reflex-based system. We confirmed that our proposed PWLS method can find functions of energy-efficient parameters over various speeds compared to the LS method. Based on these results, future research should focus on identifying essential factors of reflex circuits that contribute to enhancing energy efficiency in a wide range of locomotion speeds.

Acknowledgements

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