A Novel Controller for Bipedal Locomotion Integrating Feed-Forward and Feedback Mechanisms

Xiaofeng Xiong, Massimo Sartori, Strahinja Dosen, José González-Vargas, Florentin Wörgötter and Dario Farina

Abstract It has been recognized that bipedal locomotion is controlled using feed-forward (e.g., patterned) and feedback (e.g., reflex) control schemes. However, most current controllers fail to integrate the two schemes to simplify speed control of bipedal locomotion. To solve this problem, we here propose a patterned muscle-reflex controller integrating feed-forward control with a muscle-reflex controller. In feed-forward control, the pattern generator is modeled as a Matsuoka neural oscillator that produces four basic activation patterns that mimic those extracted experimentally via electromyograms (EMGs). The associated weights of the patterns for 16 Hill-type musculotendon units (MTUs) are calculated based on a predictive model of muscle excitations under human locomotion. The weighted sums of the basic activation patterns serve as the pre-stimulations to muscle-reflex control of the Hill-type MTUs actuating a 2D-simulated biped. As a result, the proposed controller enables the biped to easily regulate its speed on an even ground by only adjusting the descending input. The speed regulation does not require re-optimizations of the controller for various walking speeds, compared to pure muscle-reflex controllers.

1 Introduction

Modeling control mechanisms underlying speed control of bipedal locomotion is a fundamental problem in neuromechanics. This is because most methods are based on muscle-reflex controllers (MRCs) with no feed-forward control mechanisms (e.g.,

---

X. Xiong (✉) · M. Sartori · S. Dosen · D. Farina
University Medical Center Göttingen, Göttingen, Germany
e-mail: xiaofeng.xiong@phs.uni-goettingen.de

J. González-Vargas
Neural Rehabilitation Group, Cajal Institute, Spanish National Research Council,
Madrid, Spain

F. Wörgötter
Bernstein Center for Computational Neuroscience (BCCN), The Third Institute of Physics,
Georg-August-Universität Göttingen, Göttingen, Göttingen, Germany

J. Ibáñez et al. (eds.), *Converging Clinical and Engineering Research on Neurorehabilitation II*, Biosystems & Biorobotics 15,
DOI 10.1007/978-3-319-46669-9_49

central pattern generators (CPGs)) [1]. The MRCs produce walking that is not only robust to perturbations, but also characterized with muscle activations and joint angles that are surprisingly comparable to those observed in humans. However, the feedback-based MRCs are not robust to changes in the walking speed; typically, they are optimized for a single speed. This is unlike animals and humans, which regulate speed via descending signals that originate from cortical and spinal regions of the central nervous system (CNS). Inspired with this, we here propose a patterned muscle-reflex controller (PMRC) combined with a forward dynamics musculoskeletal modeling formulation driven by muscle primitives [2].

This results in a novel closed-loop modeling formulation that synthesizes the neural integration of afferent/efferent commands for the stable control of muscle-actuated simulations. We demonstrate this formulation in a 2D biped actuated by 16 Hill-type muscle-tendon units (MTUs).

2 Materials and Methods

Figure 1 shows our proposed PMRC modeling formulation. In this, the pattern generator and formation components produce baseline MTU activations for a given target locomotion condition, i.e. target speed and ground elevation. Baseline activation are further modulated by the MRC to achieve a new activation set that ensures locomotion stability.

2.1 Pattern Generator

The pattern generator is modeled as a Matsuoka neural oscillator consisting of four mutually inhibiting neurons. The oscillator is given by:

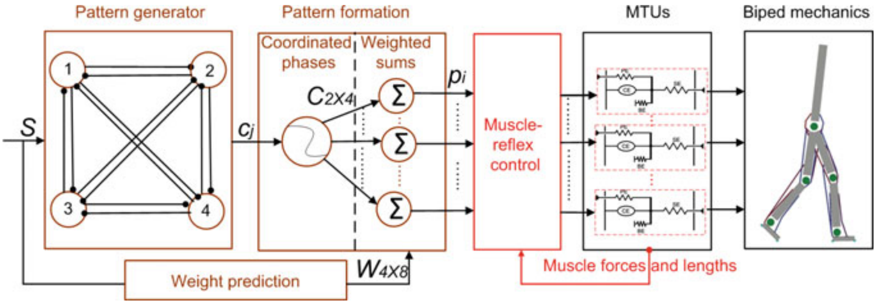

Fig. 1 Patterned muscle-reflex control (PMRC) for bipedal locomotion. Via the speed input S, feed-forward control outputs the pre-stimulations p_i ($i = 1, 2, \ldots, 15, 16$) to muscle-reflex control of 16 Hill-type MTUs actuating a biped

$$S\frac{dx_j}{dt} + x_j = -\sum_{h=1}^{4}(a_{jh}c_h) + I_j - bf_j, \tag{1}$$

$$c_j = max(0, x_j), \tag{2}$$

$$SG_j\frac{df_j}{dt} + f_j = c_j, \tag{3}$$

where a_{jh} is a weight of inhibitory synaptic connection from the h-th neuron to the j-th neuron ($j = h = 1, 2, 3, 4$), which is set as: $a_{jj} = 0$, $a_{13} = a_{24} = a_{32} = a_{41} = 1.5$, and other $a_{jh} = 2.0$. I_j and G_j are the constant input and gain to the j-th neuron, which are set as: $I_j = G_j = 1.6$. S and c_j are the input and output of the pattern generator. Adjusting the speed input S results in the outputs c_j with different oscillations (see Fig. 1), which leads to a simple strategy of speed control of bipedal locomotion.

2.2 Pattern Formation

The pattern formation is to transform the basic activation patterns c_{1-4} (see Fig. 2) to the pre-stimulations p_i ($i = 1, 2, \ldots, 15, 16$) for 16 Hill-type MTUs actuating the biped. First, the phase difference of the basic activation patterns c_{1-4} for the Hill-type MTUs actuating its left and right legs is set to one-half of the cycle (see Fig. 3). Second, the pre-stimulation matrix $P_{2\times8}$ is the product of the pattern matrix $C_{2\times4}$ and the weight matrix $W_{4\times8}$ (see Fig. 1),

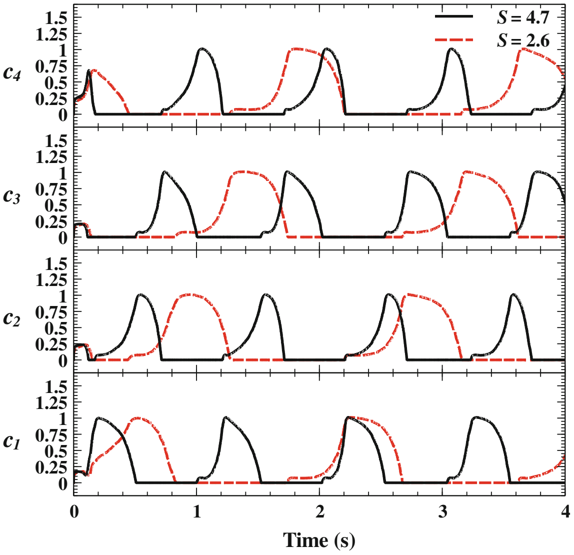

Fig. 2 Outputs c_{1-4} of the Matsuoka neural oscillator (see Fig. 1) with respect to the speed input S

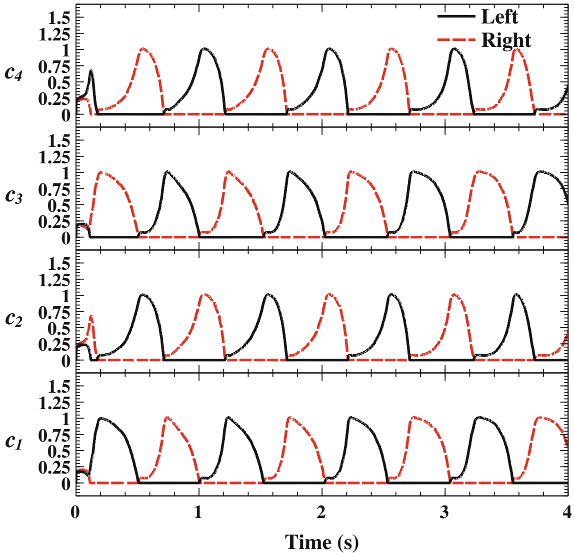

Fig. 3 Basic activation patterns c_{1-4} of the Hill-type MTUs for coordinating the left and right legs of the biped ($S = 4.7$)

$$P_{2\times 8} = C_{2\times 4} W_{4\times 8}, p_{1-8} = P_{1,1-8}, p_{9-16} = P_{2,1-8}, \tag{4}$$

where the first and second rows of $C_{2\times 4}$ represent the basic activation patterns for the 16 Hill-type MTUs actuating the left and right legs (see Fig. 3), respectively. The eight columns of $W_{4\times 8}$ denote the eight sets of weights for the eight Hill-type MTUs actuating each leg of the biped (e.g., see Fig. 4). The considered MTUs are GMAX (gluteus maximus), ILPSO (iliopsoas), HAMS (biarticular hamstrings), RF

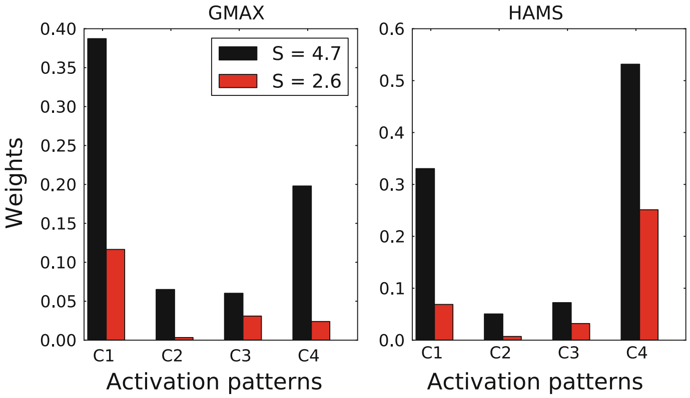

Fig. 4 Adaptive weights $W_{1-4,1}$ and $W_{1-4,3}$ for the GMAX and HAMS muscles with respect to different desired speeds [km/h]. The associated activation patterns of the adaptive weights can be seen at Fig. 2

(rectus femoris), VAS (vasti), GAS (gastrocnemius), SOL (soleus), TA (tibialis anterior). The calculation of $W_{4\times 8}$ is based on a predictive regression model where the relationship between muscle weights and walking speeds is generalized [3].

3 Results

The PMRC (see Fig. 1) enables the biped to easily regulate speed via a simple strategy where the neural oscillator and weight prediction are integrated into feed-forward control [2], and further adjusted via muscle reflex rules. This is because feed-forward control of the PMRC can easily produce activation oscillations (see Fig. 2) and leg coordination (see Fig. 3) while producing adaptive weights for their associated activation patterns with respect to speeds (Fig. 4). As a result, bipedal locomotion does not need to be re-optimized in order to walk at a different speed. The video of speed control of the biped under the PMRC can be seen at https://www.youtube.com/watch?v=z_iU89xYKX0&feature=youtu.be.

4 Discussions and Conclusions

The feed-forward neural and feedback-driven muscle-reflex control is integrated to facilitate speed control of bipedal locomotion. The method provides a way forward to understand bipedal locomotion and develop intelligent assistive devices. This approach enables synthesizing important neuromechanical processes underlying human locomotion. Future work will extend this method by synthesizing the neuro-mechanical processes underlying modulation of joint viscoelasticity [4]. It is expected this will enable achieving adaptive locomotion not only to speed but also across a variety of terrains.

Acknowledgments The work was supported by the ERC Advanced Grant DEMOVE [267888].

References

1. T.W. Dorn, J.M. Wang, J.L. Hicks, S.L. Delp, Predictive simulation generates human adaptations during loaded and inclined walking. PLoS ONE, **10**(4), 1–16, 04 (2015)
2. M.Sartori, L. Gizzi, D.G. Lloyd, D. Farina, A musculoskeletal model of human locomotion driven by a low dimensional set of impulsive excitation primitives. Frontiers in Computational Neuroscience, **7**(79) (2013)
3. J. Gonzalez-Vargas, M. Sartori, S. Dosen, D. Torricelli, J.L. Pons, D. Farina, A predictive model of muscle excitations based on muscle modularity for a large repertoire of human locomotion conditions. Front. Comput. Neurosci. **9**(114) (2015)
4. M. Sartori, M. Maculan, C. Pizzolato, M. Reggiani, D. Farina, Modeling and simulating the neuromuscular mechanisms regulating ankle and knee joint stiffness during human locomotion. J. Neurophys. (2015)