Neuromechanical simulation of human locomotion: descending modulation of spinal reflex parameters during speed changes

Andrea Di Russo, Anne D. Koelewijn, Florin Dzeladini, Auke J. Ijspeert
Biorobotics Laboratory, EPFL – École Polytechnique Fédérale de Lausanne
andrea.dirusso@epfl.ch, *anne.koelewijn@epfl.ch*, *florin.dzeladini@epfl.ch*, *auke.ijspeert@epfl.ch*

1 Introduction

The structure of their neural and biomechanic systems allows animals and humans to walk smoothly with minimal involvement of conscious control, even though locomotion is a highly complex motor task [1]. Locomotion is controlled in a hierarchical way: the spinal level generates muscle excitation patterns by combining feedforward pattern generators with sensory feedback [2], while the brain modulates the spinal control based on desired gait characteristics (e.g. speed and direction) [3] [4]. However, little is known about the exact role of different brain areas in control of human locomotion and the interaction between descending pathways and spinal network. Yet, the pathological gaits resulting from brain lesions (e.g. stroke and cerebral palsy) show that abnormal descending pathways may lead to muscle weakness and spastic behavior [5]. Therefore, the brain contribution is essential to achieve efficient walking patterns.

Numerical simulations of robust gaits generated by central pattern generators (CPGs) [6], spinal reflexes [7] and combinations of both [8] [9] result in realistic, human-like locomotor patterns. However, these studies have only investigated the mechanism of motor control at the spinal level, and therefore can only generate gait with specific characteristics such as defined speed, step length, step frequency and ground clearance.

Our overarching goal is to understand the role of different brain areas on locomotion control. Towards this goal, descending modulation signals from the brain should be included in gait simulations. In simulation, the effect of changing the characteristics of the descending modulation can be studied, which will lead to a better understanding of the role of different brain areas in gait. In the current abstract, we aim to investigate how descending modulation signals modulate spinal circuit parameters to generate desired speed.

2 Methods

The human model and the reflex control was based on [7]. The human model is a sagittal plane musculoskeletal model with seven segments: the trunk, the left thigh, shank and foot, and the right thigh, shank and foot [8]. It is operated by seven Hill-type muscles in each leg, with parameters as given in [7]. Muscle stimulation is controlled with reflexes. Positive feedback activates the vastus, soleus, and gastrocnemius during stance, and the gluteus and hamstrings during swing. Length feedback activates the tibialis anterior during stance and swing and the psoas during swing. The gluteals, hamstrings, and psoas are also activated based on feedback of the trunk orientation. Hyperextension of the knee is avoided by inhibition of the vastus after a joint angle threshold [7].

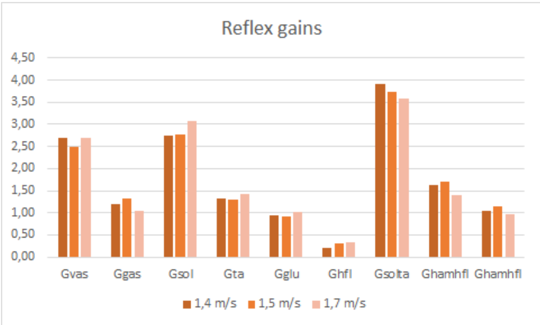
The parameters associated with the reflex controller are the basal stimulation of muscles, the gain of force and stretch reflexes and muscles' offset length, indicated with $S_{0,m}$, G_m and $l_{off,m}$, respectively. Moreover, another parameter regulating key gait characteristics is q_{ref} that represents the forward lean angle of the trunk and it is achieved through a PD controller applied to hip muscles with parameters k_p and k_d. Then, k_φ and ϕ_{off} prevent the hyperextension of the knee inhibiting the vastus muscle beyond ϕ_{off}. k_{bw} and ΔS are parameters acting on hip and vastus muscles to enable swing initiation in the late stance leg during double support. Each parameter set will achieve a gait with a specific speed. Parameters were optimized for three different speeds: 1.4, 1,5 and 1.7 m/s. Optimizations were performed with a particle swarm algorithm with a lexographic extension to handle the multiple objectives of maximizing distance, achieving the target speed, and minimizing activation and passive torques due to joint angles being outside the range of motion. This method has already been used in previous studies to construct a model of human walking [8].

The multibody dynamics were simulated in Webots (Cyberbotics Ltd., Lausanne, Switzerland), while the muscle dynamics were simulated in CasADi [10]. The reflex controller was coded in Python 2.7.

The parameter values of the different speeds will be compared. The results are analyzed to identify the parameters that are more affected by the changing of speed and, therefore, more affected by tuning activity of descending pathways.

3 Results

A sensitivity analysis conducted studying the changing of single parameters and the global effect on gait pattern showed that reflex gains are the ones that more affect



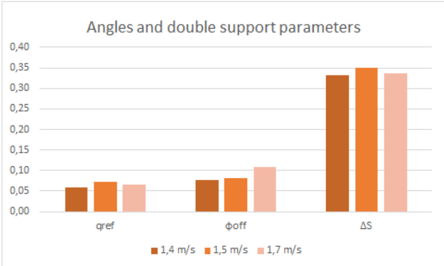


Figure 1: Reflex parameters changing in 3 different ranges of speed

the speed of the model. On the other hand, no significant changes were observed in other parameters except for the forward lean angle of the trunk and the offset angle of the knee given by q_{ref} and ϕ_{off}, respectively. Therefore, only results on parameters that are shown to be relevant are presented in this abstract.

Figure 1 illustrates the changing of reflex gains among the three different ranges of speed. The only flexor muscle that exhibits a gradient behavior in accordance with speed is the hip flexor. Indeed, the increasing tendency of this reflex gain in swing allows larger step length with higher velocity values. On the other hand, the main extensor muscles, soleus and gluteus maximus, show increasing values of their gain reflexes according to increasing of speed allowing more propulsion to the body.

The other relevant parameters' behaviors are described in the second bar plot of Figure 1. ϕ_{off} increases his value according to the positive gradient of speed. By contrast, q_{ref} and ΔS do not show a positive or negative gradient with the increasing of velocity.

4 Discussion

The results for the reflex gain parameters described in the first plot in 1 are coherent with the theoretical knowledge of human locomotion. Indeed, the increasing gains of soleus and gluteus maximus reflexes give the propulsion required in stance to increase velocity. Moreover, the soleus is known to be the main propulsion muscle in biped walking [11]. In addition, the increasing stretch reflex gains of the hip flexor in swing gives an higher flexion of the hip leading to a larger step length. Furthermore, the offset angle of the knee also increased with speed. This, may be due to a major tendency of over extension of the knee when extensor gains are higher at larger speeds. However, this major extension is not found on the values of the reflex gain of the vastus muscle G_{vas}. On the other hand, the forward lean angle of the torso does not follow either a positive or negative gradient with increasing of speed. This is an unexpected result since the inclination of the torso should increase with velocity [12]. Therefore, these results need to be investigated further.

A deeper analysis is required to better understand the modulation of speed in gait. We aim to study a larger speed range to see if the reported speed effects are present in a larger range as well. The goal is to create a model of descending modulation using a machine learning approach. As part of this, it will be investigated which parameters of the reflex model are different, and thus should be optimized at different walking speeds.

In conclusion, the current preliminary results describe part of the possible strategies adopted by brain areas to modulate speed, but more results are needed to understand the interaction between descending drive and spinal circuits.

Acknowledgements

This work is supported by the Swiss National Science Foundation through Sinergia project 177179.

References

[1] Duysens Jacques and Henry W.A.A. Van de Crommert. Neural control of locomotion; part 1: The central pattern generator from cats to humans. *Gait posture*, 7.2:131–141, 1998.

[2] Sten Grillner. Control of locomotion in bipeds, tetrapods, and fish. *Handbook of physiology. The nervous system. Motor control*, 2.Part 2:1179–1235, 1981.

[3] Silvia Arber and Rui M. Costa. Connecting neuronal circuits for movement. *Science*, 360.6396:1403–1404, 2018.

[4] Aftab E. Patla, et al. Visual control of locomotion: strategies for changing direction and for going over obstacles. *Journal of Experimental Psychology: Human Perception and Performance*, 17.3:603, 1991.

[5] Gerard E. Francisco Li, Sheng and Ping Zhou. Post-stroke hemiplegic gait: new perspective and insights. *Frontiers in physiology*, 9:1021, 2018.

[6] Gentaro Taga. A model of the neuro-musculo-skeletal system for human locomotion. *Biological cybernetics*, 73.2:97–111, 1995.

[7] Hartmut Geyer and Hugh Herr. A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities. *Transactions on neural systems and rehabilitation engineering*, 18.3:263–273, 2010.

[8] Jesse Van Den Kieboom Dzeladini, Florin and Auke Ijspeert. The contribution of a central pattern generator in a reflex-based neuromuscular model. *Frontiers in human neuroscience*, 8:371, 2014.

[9] Renaud Ronsse Nicolas Van der Noot, Auke J Ijspeert. Biped gait controller for large speed variations, combining reflexes and a central pattern generator in a neuromuscular model. *2015 IEEE International Conference on Robotics and Automation (ICRA)*, IEE, 2015:6267–6274, 2015.

[10] Joel Andersson. A general-purpose software framework for dynamic optimization. *Diss. PhD thesis, Arenberg Doctoral School, KU Leuven, Department of Electrical Engineering (ESAT/SCD) and Optimization in Engineering Center, Kasteelpark Arenberg 10, 3001-Heverlee, Belgium*, 2013.

[11] Jinger S. Gottschall and Rodger Kram. Energy cost and muscular activity required for propulsion during walking. *Journal of Applied Physiology*, 94.5:1766–1772, 2003.

[12] A. L. F. Thorstensson, et al. Trunk movements in human locomotion. *Acta Physiologica Scandinavica*, 121.1:9–22, 1984.