

Neuromechanical Control for dynamic bipedal walking with reduced impact forces

Johannes Widenka¹, Xiaofeng Xiong¹, Jan-Matthias Braun², Florentin Wörgötter^{1;2†} and Poramate Manoonpong^{1;2;3}

¹Bernstein Center for Computational Neuroscience, Institute of Physics III, University of Göttingen, Göttingen, Germany. (Email: johannes@widenka.de, Xiaofeng.Xiong@phys.uni-goettingen.de, worgott@gwdg.de)

²Bernstein Focus Neurotechnology, University of Göttingen, Göttingen, Germany. (Email: jbraun@physik3.gwdg.de)

³CBR Embodied AI & Neurorobotics Lab, The Maesk Mc-Kinney Moller Institute, University of Southern Denmark, Odense M, Denmark. (Email: poma@mmpi.sdu.dk)

Abstract: Human walking emerges from an intricate interaction of nervous and musculoskeletal systems. Inspired by this principle, we integrate neural control and muscle-like mechanisms to achieve neuromechanical control of the biped robot RunBot. As a result, the neuromechanical controller enables RunBot to perform more human-like walking and reduce impact force during walking, compared to original neural control. Moreover, it also generates adaptive joint motions of RunBot; thereby allowing it to deal with different terrains.

Keywords: dynamic walking, virtual muscle-like mechanism, human-like walking, RunBot, neuromechanical control

1. INTRODUCTION

Compliant, stable and dynamic locomotion is common to muscle driven locomotion. Especially humans are exemplary bipedal walkers. After a rather long training period in childhood, their gait has a lot of advantageous properties: It is energy-efficient and has damping properties to protect the skeleton and especially the spinal cord while still maintaining a firm foothold and adaptivity to a variety of circumstances like slopes, rough terrains and different surface materials and locomotion speeds.

Implementing this human-like walking onto robotic applications is very promising, though, the complexity of the used methods should be kept as low as possible in order to maintain transferability of the solution and to simplify the configuration and control of the resulting robot controller. In [8] it is stated that muscles, despite their function as linear actuators have intrinsic self-stabilizing properties that together with neural control and the mechanical properties of the limbs form up the final movement.

Motivated by the idea of integrating the spring/damper-like properties of muscles into robotic systems, solutions emerged that make use of bulky and heavy mechanical components that imitate muscles in a physical way like it was done in [9]. Also integrating virtual spring/damper systems into the controlling software, used to maintain constraints for the robots pose were investigated, but usually require a careful definition and analysis of the overall system in order to map the effect of the virtual springs and dampers onto the required motor signals correctly [1].

In order to understand the interplay of neural control, mechanical properties and muscle-like mechanisms and their influence on bipedal walking behaviour, our approach as well is to integrate these mechanical components virtually, but local to each controlled actuator in a strongly simplified way.

Following the biological example, we developed a framework producing virtual muscle-like behaviour and apply it to a bipedal robot system controlled based on simple reflexes with a small neural network. As a step into the direction of human-like walking we assess virtual muscle-like mechanics ramifications on impact reduction during the gait cycles and the robots ability to tackle more challenging environments.

2. NEUROMECHANICAL CONTROL OF THE RUNBOT SYSTEM

The RunBot system has been developed during the last ten years[3, 5]. Its original system consist of biomechanical structures and neural control. In this study, we extend it by integrating muscle-like mechanisms into it, resulting in neuromechanical control which is inspired by human locomotion control.

The neuromechanical controller (fig.4) consists of a reflexive neural network and biomechanical mechanisms, each of which is described below.

2.1. Biomechanics

2.1.1. The biomechanical structures of RunBot

”RunBot”, firstly developed in 2005 in order to study biologically inspired neural control exploiting the same mechanics as passive walkers do, is a realization of a 2d two-legged robot and was probably the first dynamic walking biped, controlled only by a reflexive controller [3]. The components of the robotic system are depicted in figure 1. The real robot, and its graphical representation in a computer simulation based on the simulation framework lpzrobots[7] are shown in figure 2.

All servo motors actuating the joints are modified in a way, that each serves as both: a sensor reading the current angular joint position and a DC motor actuating the joint via a gear. This is achieved by removing the internal controller that usually maintains the target joint position that is forwarded to the servo motor as control signal.

† Florentin Wörgötter is the presenter of this paper.

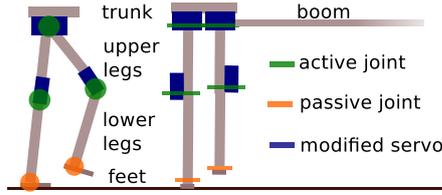


Fig. 1: Schematic RunBot and its components in sideview (left) and frontview (right). The passive joint is actuated by a torsion spring, while the active joints are driven by modified servo motors. The boom stabilizes the robot sagittally, such that it is controlled to move planarly the circular path.

The modifications result in a voltage controlled joint with decent friction generated by the gear. In addition, two switches stored in the lower leg are used in order to serve as a binary foot contact signal.

As a consequence of this design, RunBot's mechanics enable energy-efficient walking. For one thing, RunBot is able to continue moving its joints without actuation by inertia in applying low or no voltage to the DC motors. Only the gears friction brakes the movement slowly. For another thing the flat feet actuated by the torsion springs enable natural, smooth and energy efficient supports of the legs during stance phases while complying to smaller obstacles hit during swing phase[5].

2.1.2. Muscle-like mechanisms

The muscle-like mechanisms called the virtual agonist-antagonist mechanic (VAAM) being used here, previously has been applied to the hexapod robot AMOSII and its great effects on the systems abilities to adapt to different walking environments and the largely enhanced compliance were shown in [10]. In contrast to similar approaches simulating a combination of virtual springs and dampers for a whole robotic system or series of joints, thereby carefully defining constraints for the produced gait and the robots pose[1, 4], the VAAM does not require complex analysis of the dynamical system. VAAM is applied locally to each joint with the goal to manipulate the joints control signals in a way as if it was controlled by two antagonistic muscles. Only minimal information of the rest of the system is required in order to define the virtual muscles. This locality greatly improves the model's transferability to other systems.

Figure 3 visualizes the involved model components. It shows a joint moving a shank that is, on the other end, affected by an external force. This is, for instance, the force generated by the body's weight when it is supported by the shank.

The resulting total torque τ acting on joint j is defined in equation 1.

$$\tau_j = \sin(\theta) \cdot L \cdot F^{ext} + r \cdot \alpha \cdot C + 2 \cdot r^2 (K\theta + D\dot{\theta}), (1)$$

where θ and $\dot{\theta}$ is the current joint angle relative to the relaxed joint position and its derivative in time, L the length of the muscle, r the distance of the muscles leverage point

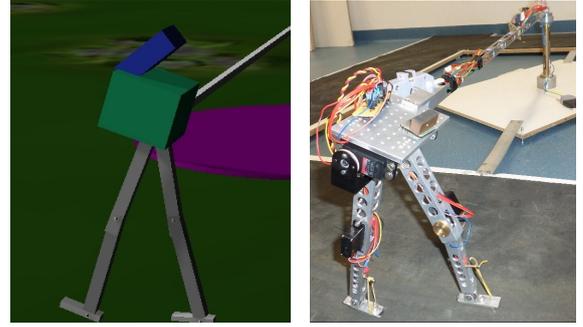


Fig. 2: Left: The visualization of a simulated RunBot with adjustable upper body component used to simulate leaning and disturbance. Right: The real robot during walking with a small static weight mounted on the trunk.

to the rotation point, α the bipolar sum of both muscles activation and C a constant scaling factor. K and D are the stiffness and damping parameters for both muscles.

For the details about the VAAM, please see the extensive literature [10].

Since the original implementation of the VAAM was done solely for position controlled joints, in order to improve usability of the model, a general framework was designed enabling the application of VAAM to any kind of active joint actuator. The major changes for RunBot compared to VAAM on the hexapod [10] are enlisted below:

- The deactivation of the model during swing phase is replaced by a smooth stiffness transition to 40% of its original value when the foot contact switch signalizes a swinging leg. K starts to recover as soon as the foot has ground contact again. Thus through all phases the VAAM is used to control the joints, but with varying stiffness.
- The relaxed muscles position may now differ from the joint angle pointing towards the point of external force application. For the knees, for instance, the joint point towards the ground at 180° but the relaxed muscle position is at 175° .

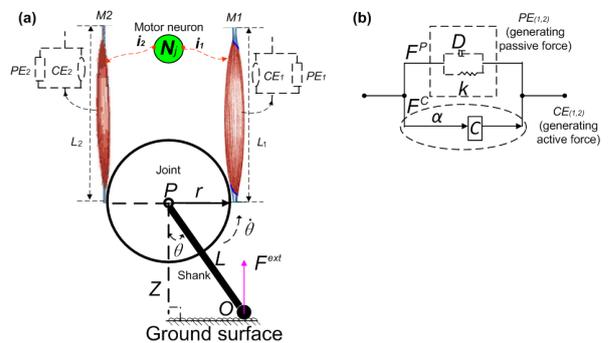


Fig. 3: a) VAAMs applied on a joint. All parameters are part of the model and the muscles apply virtual force on the joint that is converted to motor signals in the end. b) Muscle forces: The parallel element (PE) simulated by a spring/damper system and the contractile element (CE) representing the actively generated torque.

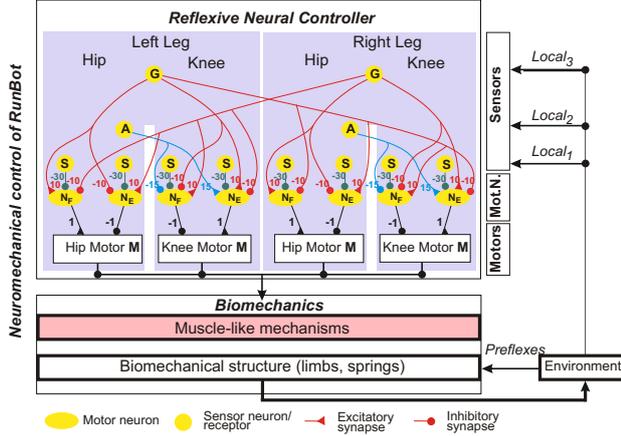


Fig. 4: The complete closed control loop for the biologically inspired neuromechanical controller.

- The torque generated by the external force is estimated by taking all angles and shank lengths of the chained joints into account, thus, the hip and the knee VAAM exchange required information. The robots weight is distributed equally among all ground touching legs.
- Due to an unknown voltage-torque characteristic curve for the motors, as a rough estimate, the VAAMs total torque is assumed to be proportional to the potential applied to the motor.

2.2. The reflexive neural network

The controller based on the ideas of Cruses model[2] is a realization of a small artificial neural network (fig 4), simulated with non-spiking neurons.

The outcome of the neural network, represented by one flexor and one extensor motor neuron for each hip and knee is primarily determined by two reflexes. The foot contact sensor triggers the retraction of the ipsilateral hip and the contralateral knee and moves the contralateral hip forwards while contracting the knee by exciting the respective flexor and extensor motor neurons. The phase transition is caused by the stretch sensor neuron activated in anterior extreme hip positions, utilizing agonist excitement and antagonistic inhibition.

The resulting motor signals are the scaled differences of the respective motor neurons activation. The synaptic weights are chosen in such a way that the motor receives zero input during some time of the walking cycle and thus, the respective joint is moved only passively during mid-swing leg and mid-stance phase.

3. ROBOT WALKING EXPERIMENTS

The selection of experiments presented in this article is mainly used in order to illustrate the potential of the VAAM for robotic applications, especially referring to adaptive and stable dynamic locomotion.

For all experiments the same reflexive controller and parameter setup was used. On experiments with the muscle-like mechanisms, VAAMs were used for both, the

knee and the hip motors.

3.1. Simulations

The performance of the neuromechanical controller was evaluated first in simulation.

Figure 5 shows the acceleration measured during walking on flat ground. It is clearly visible, that the acceleration peak on heel-strike, which is the most sudden upwards acceleration during walking is decreased when VAAMs are applied to the model. Over the whole experiment, consisting of 62 s walking, the mean of the acceleration measured on heel-strike for only the reflexive controller is 0.8 with a standard deviation of 0.23. For the controller utilizing VAAM the mean acceleration is 0.4 with a standard deviation of 0.09. Thus, the acceleration could be halved and stabilized to a fixed acceleration. It should be noted, that even though the controller with enabled VAAMs produces shorter steps, the parameters were adapted in such a way, that both controllers produce approximately the same locomotion speed.

Another series of experiments was executed in order to investigate the extended controller's walking performance on slopes and irregular terrain. Without touching the leaning of the robot in utilizing a moveable weight like it was done in [6], only relying on the reflexive controller the biped was not able to cope with the environments it was exposed to. Extending the controller with the muscle-like mechanisms enabled the robot to walk reproducibly on a 2% slope upwards, on a 8% slope downwards and as well on a track with smaller steps.

The parameters being tuned for the experiments were the muscle stiffness for knee and hip joints and the virtual mass of the robot determining the external force virtually load onto the joints of a ground touching leg. It turned out that different parameters are differently suitable for various environments. While the virtual mass appears to control the general leaning of the robot, the knee stiffness limits the robots acceleration with increasing values and the hip stiffness can be utilized in order to increase the speed while decreasing the stride length with higher stiffness.

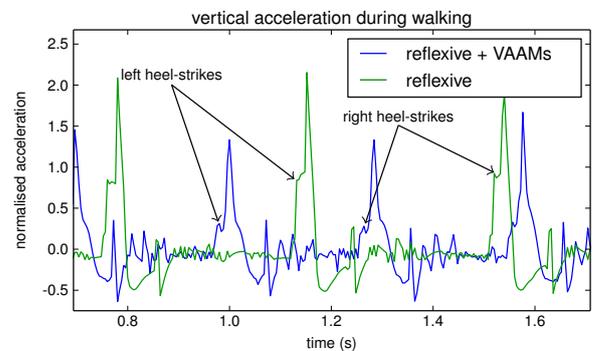


Fig. 5: Vertical acceleration the trunk is exposed to during walking, recorded on two independent runs. When the heels hit the ground, sudden positive acceleration occurs and is identified by the first of two peaks at a time.

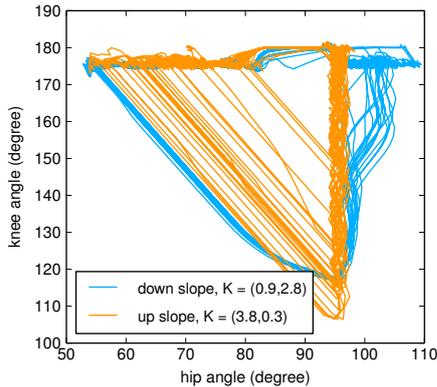


Fig. 6: Phase diagram of the joint angles during upwards and downwards walking. For both experiments, the stiffness is tuned suitable to the environment. K given in tuples with (K_{Hip}, K_{Knee})

Figure 6 shows the different gaits being generated for upwards and downwards walking. For upwards walking, some strides are very short, depending on the time point where the swinging foot touches the ground. Downwards walking results in very long strides, whilst the hip is moved into hyperextension sometimes due to the larger impact on heel-strike. Recordings of the simulation experiments are available in the internet¹.

3.2. Preliminary results on the real robot

First experiments on the real robot seem to confirm the observations that have been made in simulation. The stiffer the hip muscles are tuned, the shorter the strides become while increasing the robots locomotion speed. On smaller slopes it was advantageous to stiffen the knee muscles and to relax the hips in order to prevent the robot from falling forwards, while too stiff knees cause RunBot’s feet to hit the ground during mid-swing. Also walking on slightly irregular terrain and tackling smaller slopes was enhanced with VAAMs.

While extensive experiments in order to obtain statistically relevant data are still pending, video recordings of the real robot used to compare the controllers can be accessed online¹.

4. CONCLUSION AND FUTURE WORK

In this article, we successfully extended the neural controller with the virtual agonist-antagonist mechanism, originally designed for a servo motor actuated, hexapod robot. It exhibited more natural gaits, tunable through the stiffness parameters of the hip muscles and knee muscles. This way, without changing parameters of the neural network or the body leaning, RunBot’s abilities in walking on various environments was increased, while the impact forces on heel-strike were reduced with a certain stiffness setup.

In coming research, statistically relevant data of the

real robot will be raised while it will be exposed to challenging environments. Extending the neural network such that it controls the stiffness of the muscles, for instance based on 2d-acceleration data is also very promising. Finally, the VAAMs will be applied to more robotic systems in order to explore and extend its portability.

5. ACKNOWLEDGMENTS

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¹<http://www.widenka.de/johannes/vaam/swarm/>