SICE Annual Conference 2008
August 20-22, 2008, The University Electro-Communications, Japan

Towards a general neural controller for 3D quadrupedal locomotion

Christophe Maufroy[1], Hiroshi Kimura[2] and Kunikatsu Takase[1]

[1]Graduate School of Information Systems, University of Electro-Communications, Tokyo, Japan
[2]Graduate School of Science and Technology, Kyoto Institute of Technology, Kyoto, Japan

Abstract: Our study aims at the design and implementation of a general controller for quadruped locomotion, allowing the robot to use the whole range of quadrupedal gaits. The controller design phase is carried out using simulation. This paper reports the simulation of steady walking at 0.6 m/s of both the forelegs only and the hind legs only (with a supporting structure at the back and at the front respectively), achieved using our quadrupedal model.

Keywords: Quadruped, Neural Controller, CPG, Simulation

1. INTRODUCTION

Traditional methods for legged locomotion control are generally classified into ZMP-based control and limit-cycle-based control. It was shown that ZMP based control is effective for controlling posture and low-speed walking of biped and quadruped, but is not good for medium or high-speed walking from the standpoint of energy consumption. In contrast, motion generated by the limit-cycle-based control, making use of the natural dynamics of the system, has superior energy efficiency, but there exists an upper bound of the period of the walking cycle, in which stable dynamic walking can be realized. According to this view, legged robots implementing one of these control paradigms have been constructed and good performances have been achieved. However, implementation of a general legged locomotion controller, integrating both posture control and rhythmic motion control and having the ability to shift continuously from one control method to the other according to locomotion speed, has never been reported.

On the other hand, the nervous system of legged animals gives us a wonderful example of a control system which possesses such an ability. The ultimate goal of our research is thus to use biological inspiration to develop a general neural controller allowing the robot to use the whole range of quadrupedal gaits (i.e. from low speed walking to fast running) so as to be able to choose the most appropriate gait to deal with a given environment. Our study shares similarities with the current work of Ogihara et al.[5].

In a first step of our study, we extended and improved the NPG architecture proposed by Wadden et al.[6] to use it with the musculoskeletal model of the hind legs of the cat proposed by Ekeberg et al.[2], and simulated stepping motion using a two hind legs model. Doing this, we obtained the original results of being able to induce, using that biomorphic mechanical model, autonomous speed and stepping pattern modulations according to the change of a single tonic input modeling the input from the upper neural system (Maufroy et al. [3]). In this paper, we report the results of preliminary experiments towards the development of a controller for 3D quadrupedal locomotion, i.e. the design of the four legs simulation model and the implementation and validation of a leg controller for the forelegs.

2. MUSCULOSKELETAL MODEL

For the sake of concision, the values of the parameters for the musculoskeletal model are not mentioned in this paper. Interested readers can refer to Maufroy et al. [4].

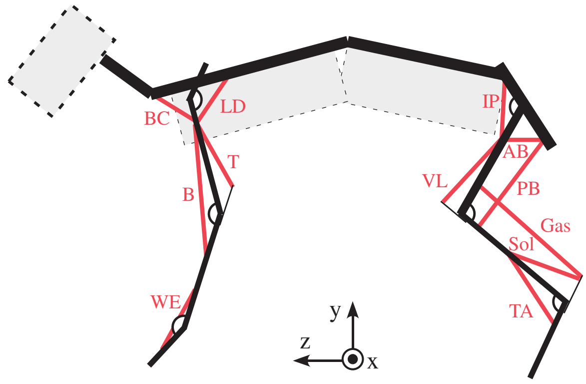

Fig. 1 Musculoskeletal model: forelegs have 3 joints and are actuated by 5 muscles (BC: Brachiocephalicus, LD: Latissimus Dorsi, B: Biceps, T: Triceps and WE: Wrist Extensor) while hind legs have 3 joints and are actuated by 7 muscles (IP: Iliopsoas, AB: Anterior Biceps, PB: Posterior Biceps and Semitendinosus, VL: Vastus Lateralis, Gas: Gastrocnemius, TA: Tibialis Anterior and Sol: Soleus).

2.1 Skeleton

Using measurements on a real cat specimen, we established the skeletal model, represented in Figure 1.

2.2 Muscle model

For the muscles, we used the model of Brown et al.[1] with parameters from Ekeberg et al.[2]. The muscle fascicles are modeled as active contractile elements (CE) in parallel with passive elastic elements (PE). The force generated by the contractile elements is scaled by the muscular activation level a_m (output by the motor neurons of the neural controller). The torques that the muscular system applies on the skeleton are computed using the muscular forces and the parameters describing the insertion of the muscles to the skeleton. Unlike in Ekeberg et al.[2], the tendons were not included in the model.

2.3 Hind legs

For the hind legs, we used the same model as Ekeberg et al.[2], made of three articulations actuated by a set of seven muscles. The parameters of the muscular system are the same except that the natural length of PB was set to 85% instead of 75%.

2.4 Forelegs

We modeled the forelegs as four links: scapula, humerus, radius and hand, with three articulations: shoulder, elbow and wrist (for the sake of simplicity, the scapula was considered to be fixed to the body). The three articulations are actuated by a set of five muscles, as represented in Figure 1. There is no muscle responsible for wrist flexion as flexion of the wrist occurs naturally when the limb is swung forwards.

3. LEG CONTROLLER

3.1 Overview of the leg controller

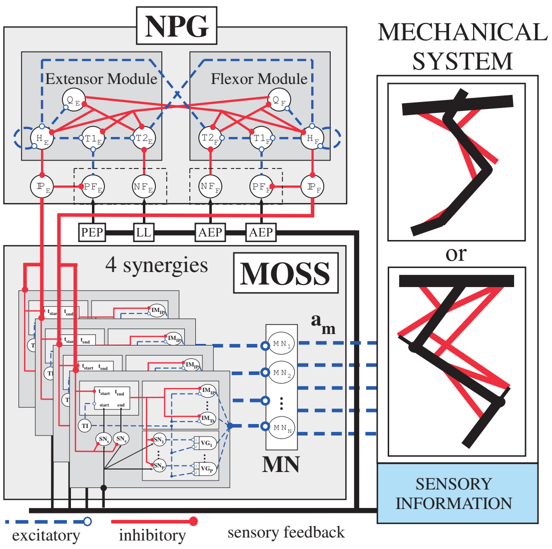

Fig. 2 Overview of the Leg Controller

In Maufroy et al. [3], we used a Leg Controller (or LC) made of three parts: a Neural Phase Generator, a Motor Output Shaping Stage (MOSS) and a Propulsive Force Control Module (PFCM). The PFCM, allowed us to induce autonomous speed and stepping pattern modulations according to the change of a single tonic input modeling the input from the upper neural system. However, in this stage of our study, as we are focusing on how quadrupedal walking can be generated and which mechanisms contribute to the stabilization of the walking pattern and coordination of the legs, we decided, for the sake of simplicity, to carry out the simulations using a fixed walking speed so that the PFCM was not included in the neural controller. The structure of the LC of one leg is represented on Figure 2

3.2 Neuron models

3.2.1 Interneurons (I)

The model of the interneurons is a slightly modified version of the implementation used in [6]. Each neuron represents a population of functionally similar neurons and its output is the mean firing frequency of the population. It is basically a "leaky integrator" with saturating transfer function and thus an output value between 0 and 1 (the maximum firing rate). Each neuron is characterized by three parameters: a time constant (τ), a gain (Γ) an activation threshold (Θ). The excitatory and inhibitory synaptic inputs are handled separately (using the presynaptic inputs from sets Ψ_+ and Ψ_- respectively):

$$\dot{\xi}_+ = \frac{1}{\tau}\left(\sum_{i\in\Psi_+} u_i w_i - \xi_+\right) \quad (1)$$

$$\dot{\xi}_- = \frac{1}{\tau}\left(\sum_{i\in\Psi_-} u_i w_i - \xi_-\right) \quad (2)$$

where w_i is the strength of the synapse i and u_i the output value from the corresponding presynaptic neuron. We added two features to the original model: the saturation of inhibitory synaptic input ($\xi_- \leq 1$) and the resetting of ξ_+ to 0 when the neuron is completely inhibited ($\xi_- = 1$). ξ_+ and ξ_- are then recombined to generate the neuron output:

$$u = \begin{cases} 1 - \exp\{(\Theta - \xi_+)\Gamma\} - \xi_- & \text{if positive} \\ 0 & \text{otherwise} \end{cases}$$

3.2.2 Sensory neurons (SN)

The neuronal model used for sensory signals transduction is the same as above except for two features. First, the excitatory synaptic input is function of s (the sensory input) and $\dot{s}$ (its derivative). Second, the output function is simpler.

$$\dot{\xi}_+ = \frac{1}{\tau}(K_p(s - s_{off}) + K_v\dot{s} - \xi_+) \quad (3)$$

$$u_{SN} = \begin{cases} min(\xi_+, 1) - \xi_- & \text{if positive} \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

where s_{off} is an offset value. Currently, four kinds of sensory information coming from the musculoskeletal model are available to the LC: the force (f_m), the length (x_m) and the contraction speed (v_m) of each muscle, as well as the contact with the ground status for each leg.

3.2.3 Motor neurons (MN)

Motor neurons simply sum the presynaptic inputs and output the sum (if it is positive).

3.2.4 Variable gains (VG)

Variable gains are building units that output the product of their two inputs (the first one being the signal and the second one the gain).

3.2.5 Tonic input neurons (TI)

These neurons output a constant value.

3.3 Neural Phase Generator

The **NPG** activity characterizes the current locomotion phase. The functional units of the NPG layer are called "modules" and accounts for the main stages of the locomotion. Transfer of activity from one module to another is under sensory control.

3.3.1 Neuronal Structure

Our NPG is made of two modules, the extensor and flexor modules (see Fig.3). Each module is made of seven neurons (five interneurons and two sensory neurons):

- **H neuron** is the neuron representative for the activity of the module. It has excitatory connections with itself (self-excitation), as well as Q and T_1 neurons. On the other hand, it inhibits the IP neuron.

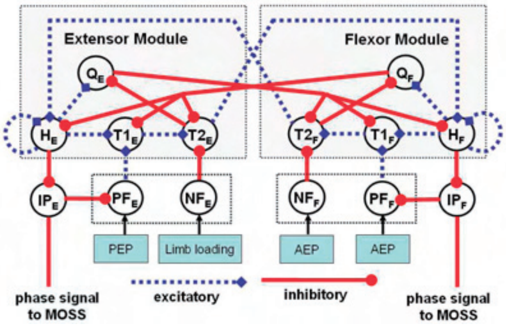

Fig. 3 Internal structure of the NPG

- **Q neuron** ensures that only one module is active at the time by inhibiting the H and T neurons of the other modules.
- **T neurons** are responsible for the transition to the next module. T_1 receives excitatory inputs from both H neuron and sensory feedback paths (through the PF neuron) while T_2 is under inhibitory sensory influence (through the NF neuron). T_1 excites T_2 which then promotes the transition by exciting the H neuron of the next module while reducing its inhibition by inhibiting the Q neuron of its own module. This organization allows to set the time constant of T_1 in order to achieve long duration of module activation without slowing down the transition when the inhibitory sensory influence on T_2 disappears.
- **IP neuron** is the complementary neuron of H: it is active when the module is inactive. It has inhibitory connections with the interneurons in the MOSS layer and with the sensory feedback having a excitatory action on the transition T neurons (gating role). When H becomes active, it inhibits IP, hence it activates the previously inhibited neurons.
- **PF and NF neurons** are the sensory neurons which relay the sensory information to the transition neurons. PF is used for the sensory feedback which promotes the transition and NF for the sensory feedback which prevents it.

Table 1 Values of the parameters used for the interneurons (top table). Subscripts E and F refer to the extensor and flexor modules respectively. The values of the parameters for the interneurons are slightly modified from Wadden and Ekeberg (1998). The parameters are the same for the fore and the hind legs.

IN	Θ	Γ	τ (ms)
$H_{\{E,F\}}$	0.1	1	10
$Q_{\{E,F\}}$	0.5	0.2	10
$T1_F$	1	0.5	50
$T1_E$	1	0.5	100
$T2_{\{E,F\}}$	0.1	1	10
$IP_{\{E,F\}}$	0.1	1	5

3.3.2 Sensory feedback

We used the same kinds of sensory information as Ekeberg et al.[2] for the sensory feedback to the NPG:

- **Anterior Extreme Position (AEP)** proximity, evaluated using the length AB for the hind legs or LD for the forelegs, is used to control the transition from the flexor to the extensor modules through excitatory and inhibitory influences on the transition neurons of the flexor module.

Table 2 Values of the synaptic weights of the connections represented on Figure 3. The first column (O) gives the neuron origin of the connection, while the second one (D) is its destination. (i) means that the destination neuron belongs to the same module as the origin neuron, while (c) means that it belongs to the other one. Finally, w is the synaptic weight of the connection. (E) and (F) refer to the extensor and flexor modules respectively.

O	D		w	O	D		w
H	H	(i)	4.0	T_2	H	(i)	-2.0
	Q	(i)	4.0		Q	(i)	-3.0
	T_1	(i)	1.0		H	(c)	3.0
	IP	(i)	-2.0	IP	PF	(i)	-2.0
Q	H	(c)	-5.0	PF	T_1	(i)	1.5 (E)
	T_1	(c)	-5.0				2.0 (F)
	T_2	(c)	-5.0	NF	T_2	(i)	-1.5
T_1	T_2	(i)	5.0				

Table 3 Values of the parameters of the sensory neurons of the NPG (up: hind legs LC - down: forelegs LC).

	s	s_{off}	K_p	K_v	τ (ms)
PF_E	x_{IP}	0.8	5	0	5
NF_E	f_{Sol}	5	1	0	5
PF_F	x_{AB}	0.6	5	0	5
NF_F	x_{AB}	0.9	-20	0	5

	s	s_{off}	K_p	K_v	τ (ms)
PF_E	x_{BC}	0.7	5	0	5
NF_E	f_T	5	1	0	5
PF_F	x_{LD}	0.7	5	0	5
NF_F	x_{LD}	0.9	-20	0	5

- **Posterior Extreme Position (PEP)** proximity, evaluated using the length of IP for the hind legs or BC for the forelegs, promotes the transition from the extensor to the flexor module.
- **Leg Loading (LL)**, evaluated using the muscular force developed by Sol for the hind legs and T for the forelegs, prevents the transition from the extensor to the flexor module, as long as the leg loading is over a given threshold.

3.4 Motor Output Shaping Stage

The MOSS is under inhibitory influences from the NPG, coming from the IP neurons of each module (see Fig.2, 3 and 4). These signals are used to select the "synergies" which can be active during the corresponding NPG phase. Four synergies are implemented (the same as the ones used in [6] and [2]). During the flexor phase *liftoff* and *swing* can be active, while during the extensor phase *touchdown* and *stance* can be active. Initiation and termination of the activity of one synergy obey to a given timing or can be triggered on the basis of sensory information. To each synergy is associated a set of constant values for the muscular activation levels (feed-forward component) and a set of sensory feedback pathways which output variable muscular activation levels according to sensory information (feedback component). The contributions of these two components are summed by the motor neurons (MN) which output the muscular activation levels for the muscular system. To each muscle of the muscular system is associated one MN. Muscles activated in a feed-forward way and sensory feedback pathways for each

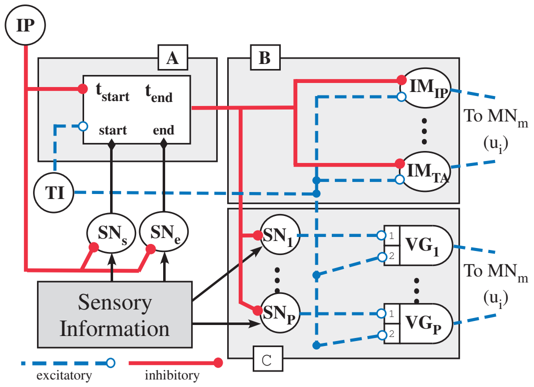

Fig. 4 Synergy structure. *A: Initiation and ending part:* synergies initiation or termination can occur following a given timing (by setting t_{start} and t_{end}), be triggered by specific sensory events (mediated by SN_s and SN_e) or use a combination of these two methods - *B: Feed-forward part:* there is one IM neuron per muscle activated in a feed-forward way, each of these neurons being connected to the appropriate MN neuron - *C: feedback part:* Each pathway involves two neurons: a SN neuron responsible of the sensory signal transduction and a VG neuron which modulates the intensity of the signal transmitted to the motor neurons MN. The muscular output levels of both the feed-forward and the feedback parts depend on the synaptic weights of the connections from the TI neuron to the output neurons (IM and VG).

synergy are represented in Figure 5. The values of the parameters used for the MOSS of the hind legs and forelegs models are given in Table 4 and Table 5. The parameters were adjusted to generate a locomotion speed of 0.6 m/s.

Table 4 Values of the synaptic weights of the connections from the TI neuron to the IM neurons in each synergy (LO: liftoff, SW: swing, TD: touchdown and ST: stance) for the hind legs model (up) and forelegs model (down). "·" means that the synaptic weight is null, i.e. that there is actually no connection between the TI neuron and the IM of this muscle in that synergy.

Syn.	IP	AB	PB	VL	Gas	Sol	TA
LO	·	·	0.2	·	·	·	0.1
SW	0.5	·	·	·	·	·	0.5
TD	0.05	·	·	0.05	0.1	·	0.5
ST	·	0.2	·	0.1	0.05	0.1	·

Syn.	BC	LD	B	T	WE
LO	·	0.15	1.4	·	·
SW	0.3	·	0.25	·	·
TD	0.4	·	0.02	0.3	0.2
ST	·	0.4	·	0.3	·

3.5 Biological grounding

Despite decades of investigation, all the details of the neural system of the cat are not yet known. Moreover, even if such knowledge was available, the complexity of the neural circuits it involves would probably until long be too prohibitive to simulate and impossible to implement on a robot. For that reasons, a trade off between simplicity and faithfulness to the biological data has to be found.

As regards the NPG, the design of the neural circuits and the

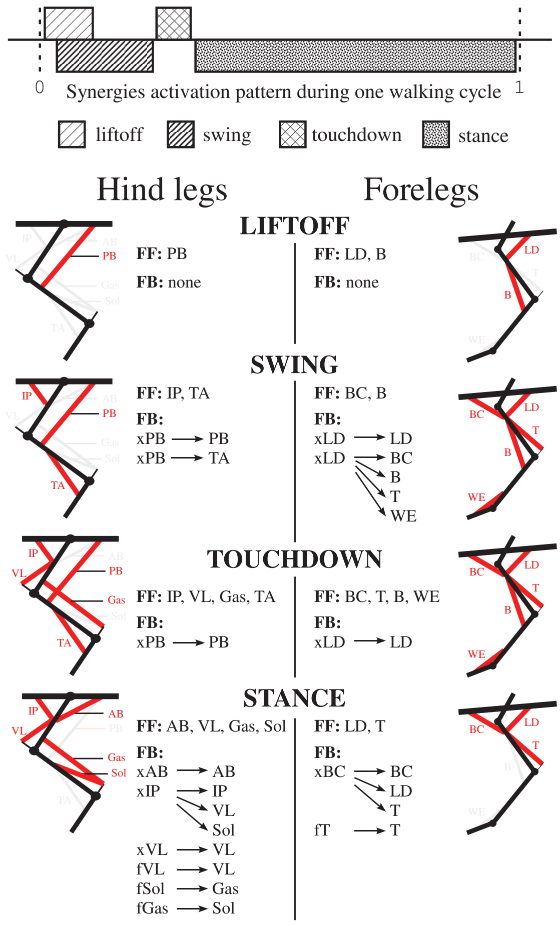

Fig. 5 *Upper part:* Example of synergies activation pattern during one stepping cycle. Liftoff starts right after the beginning of the flexor phase and is shut down soon after (65 ms for the forelegs and 50 ms for the hind legs), while swing starts a bit after the beginning of the flexor phase (60 ms for the forelegs and 10 ms for the hind legs) and last until its end. Touchdown starts right after the beginning of the extensor phase and ends when the foot touches the ground, triggering the initiation of the stance which lasts until the end of the extensor phase - *Lower part:* Muscular activity for each synergy. FF shows the muscles activated in a feed-forward manner and FB lists the feedback pathways for each synergy (on the left is the sensory signal used for the feedback and on the right the muscle which activation level is modified by the feedback pathway).

choice of the sensory signals used to trigger the phase transitions are grounded on the following biological facts:

- *After deafferentation, oscillatory patterns of extensor and flexor muscular activity still occur under pharmacological excitation* (Grillner et al. 1974): in our model, transitions between modules can occur even without sensory feedback if the synaptic weight of the connections between H and T_1 neurons are high enough to activate T_1. In that case, the NPG has an oscillatory behavior and the period of each phase depends on the synaptic weights of the connections between the neurons of the transition path and their time constants. By changing these parameters, the oscillation frequency and duty ratio could be tuned by the upper brain system. However, the neural circuit supporting this func-

Table 5 Values of the parameters of the sensory feedback pathways and their associated gain for the hind legs model (up) and the forelegs model (down). The first column gives the synergy in which the pathway is implemented. Column two to column five are the sensory input and the value of parameters of the SN neuron (see eq.(3)). Column six (m) gives the muscle whose motor neuron receives the output of the VG neuron. Finally, the last column (w) is the synaptic weight of the connection from the TI neuron to the VG neuron of the pathway.

Syn.	s	s_{off}	K_p	K_v	m	w
SW	x_{PB}	0.9	-3	0	TA	0.2
SW	x_{PB}	0	0	0.2	PB	0.04
TD	x_{PB}	0	0	0.2	PB	0.04
ST	x_{AB}	0.8	3	0.5	AB	1.0
ST	f_{VL}	0	0.007	0	VL	0.25
ST	f_{Sol}	0	0.01	0	Gas	0.25
ST	f_{Gas}	0	0.01	0	Sol	0.25
ST	x_{VL}	0.8	4	0	VL	0.1
ST	x_{IP}	0.8	2	0	VL	0.6
ST	x_{IP}	0.8	2	0	Sol	0.6
ST	x_{IP}	0.8	2	0	IP	0.2

Syn.	s	s_{off}	K_p	K_v	m	w
SW	x_{LD}	0.75	1	0	BC	0.3
SW	x_{LD}	0.75	1	0	B	-1.5
SW	x_{LD}	0.75	1	0	T	1.5
SW	x_{LD}	0.75	1	0	WE	1.0
SW	x_{LD}	0.85	5	0.2	LD	0.06
TD	x_{LD}	0.85	5	0.2	LD	0.06
ST	x_{BC}	0.8	1.5	0	LD	-4.5
ST	x_{BC}	0.8	1.5	0	BC	1.5
ST	x_{BC}	0.8	1.5	0	T	0.5
ST	f_T	0	0.003	0	VL	0.47

tion was not implemented here because we focused in this study on how the sensory feedback can contribute to the adaptive self-excited rhythm generation.

• *Transition from stance to swing is prevented as long as the hip angle is lower than a given threshold* (Grillner et al. 1978): in the condition stated above, as the intrinsic excitation from H_E to T_{E1} is too weak to evoke the transition, the excitatory input due to the PEP feedback (through PF_E) is really responsible for T_{E1} activation.

• *The extensor phase is indefinitely prolongated if the force developed by the ankle extensor muscle is over a given threshold* (Duysens et al. 1980): as long as the leg is loaded, T_{E2} is inhibited by the LL (leg loading) feedback (through NF_E), which prevents the transition to the flexor phase.

• In agreement with the conclusion of Ekeberg and Pearson (2005), LL is used as the decisive sensory information for the transition from extensor to flexor phases. Indeed, the transition cannot occur as long as T_{E2} is inhibited by the LL feedback signal, even if T_{E1} is activated by PEP sensory feedback signal.

As regards the MOSS, the muscles activated during each synergy, as well as the sensory feedback pathways, were mainly chosen while referring to patterns used by Ekeberg and Pearson (2005) for the hind legs and to data about joint kinematics and EMG patterns available in the literature for the forelegs.

4. SIMULATION RESULTS

We were able to generate steady walking at 0.6 m/s using the simulation models of Figure 6 (represented together with the data). As in Maufroy et al.[3], generation of stable stepping were achieved without explicit interaction between the leg controllers. In the case of the hind legs, the forward progression of the support is damped and generates a reaction force which is slowing down the model. This was introduced to account for the influence of the forelegs which are known to play a braking role in quadruped locomotion. Accordingly, in the case of the simulation of the forelegs, a force pushing the body forwards was introduced to account for the influence of the hind legs which are known to be responsible for the propulsion of the body. The amplitude of this force was set to be equal to the steady value of the reaction force in the simulation with the hind legs model.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we reported the extension of our musculoskeletal model to a quadruped model including the forelegs, as well as the adaptation of the neural controller that we previously used, in order to cope with the new model. Steady stepping at 0.6 m/s could be simulated with both the forelegs and the hind legs alone.

In the future, we plan to simulate quadrupedal walking by combining the fore and hind legs and using the leg controllers we developed for both of them. Preliminary experiments showed that issues such as the coordination between leg controllers and the stabilization of the rolling motion of the model have to be considered.

REFERENCES

[1] Brown, I., Scott, S., and Loeb, G. : Mechanics of feline soleus: II Design and validation of a mathematical model, *Journal of Muscle Research and Cell Motility*, 17, pp. 221-233 (1996)

[2] Ekeberg, O., and Pearson, K. : Computer simulation of stepping in the hind legs of the cat: an examination of mechanisms regulating the stance-to-swing transition, *Journal of Neurophysiology*, 94(6), pp. 4256-68 (2005)

[3] Maufroy, C., Kimura, H., Takase, K. : Towards a general neural controller for quadrupedal locomotion, *Neural Networks Special Issue 2008*, In Press.

[4] Maufroy, C., Kimura, H., Takase, K. : Towards a general neural controller for 3D quadrupedal locomotion, *Proceedings of the 20th Symposium of Autonomous and Distibuted Systems*, Suwa, (2008)

[5] Ogihara, N., Aoi, S., Sugimoto, Y., Nakatsukasa, M. and Tsuchiya, K. : Exploration of locomotory mechanism in the Japanese monkey based on an anatomically-based musculoskeletal model, Tech. Report of IEICE, 106(330), pp. 33-36 (2006)

[6] Wadden, T., and Ekeberg, O. : A neuro-mechanical model of legged locomotion: single leg control, *Biological Cybernetics*, 79, pp. 161-173 (1998)

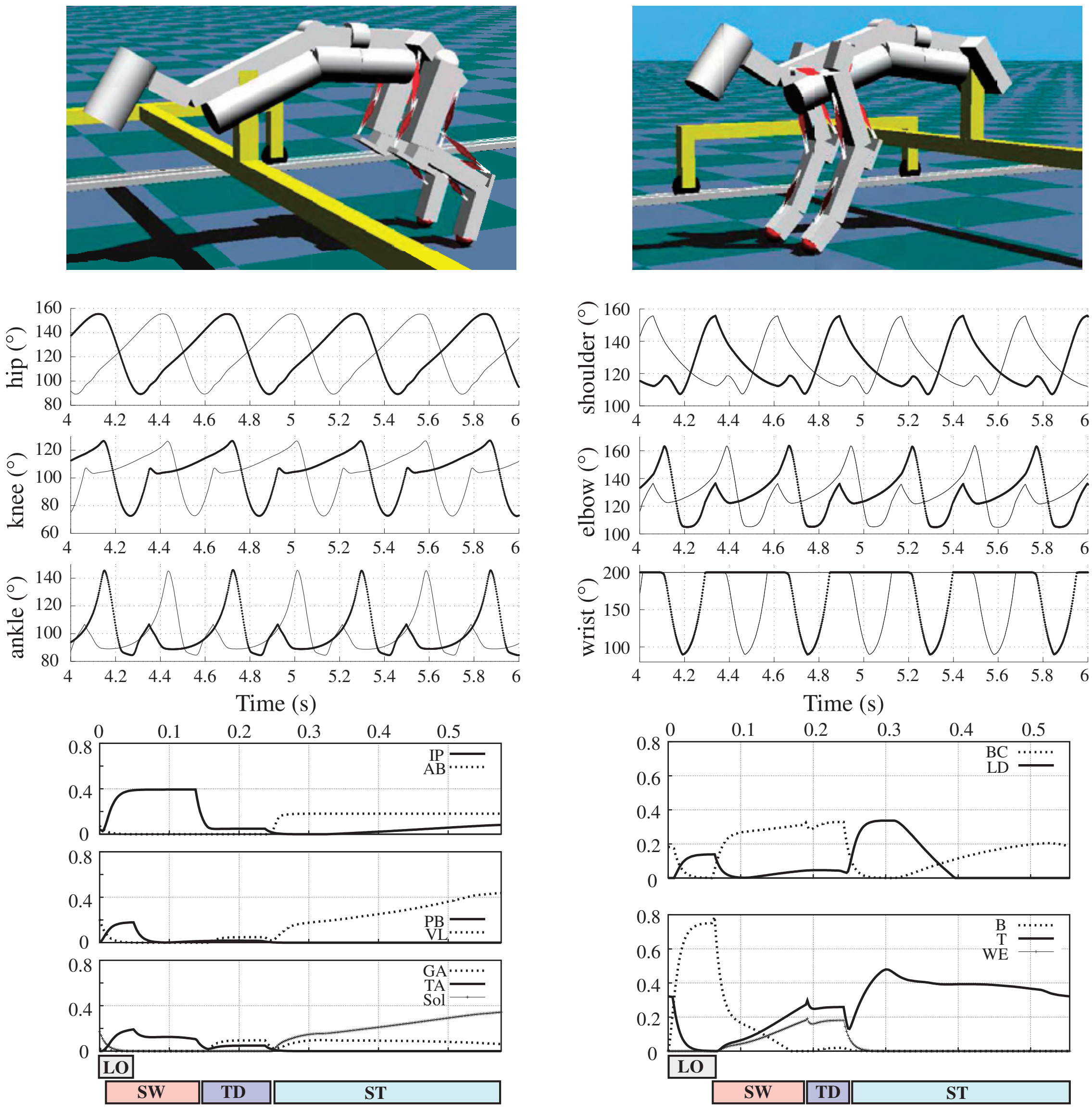

Fig. 6 Simulation models and data. *Left from up to down:* Hind legs model, joint angles and muscle activation levels for this model - *Right from up to down:* Forelegs model, joint angles and muscle activation levels for that model. The height of the supporting structure in both models was adjusted so that the front and back ends of the body were approximatively at the same heights in both simulations.