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One-Legged Locomotion with a Compliant Passive Joint

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Abstract. There is an increasing attention of exploiting compliant materials for the purpose of legged locomotion, because they provide significant advantages in locomotion performance with respect to energy efficiency and stability. Toward establishing a fundamental basis for this line of research, a minimalistic locomotion model of a single legged system is explored in this paper. By analyzing the dynamic behavior of the system in simulation and a physical robotic platform, it is shown that a stable locomotion process can be achieved without the necessity of sensory feedback. In addition, further analysis characterizes the relation between motor control and the natural body dynamics determined by morphological properties such as body mass and spring constant.

Keywords. Legged locomotion, compliance, hopping, two-segmented leg, feedforward control, morphological properties,

1. Introduction

While most of the legged robots are composed of rigid materials and controlled by high-gain control, there has been an increasing attention to the legged locomotion exploiting elastic materials.

In nature, biologists have explored a few important reasons why animals make use of elasticity to achieve rapid legged locomotion. Elastic materials can be used for storing energy which results in energy efficient locomotion [1,2]. In particular, the so-called spring-mass model has been explored for the theoretical analyses of animal running behavior [3,4]. This simple theoretical model which consists of a body represented as a point mass and a leg as a linear spring explained how the legged locomotion can be approximated.

Based on these biomechanical studies, a number of legged robots have been developed to understand how elasticity could be exploited for the purpose of locomotion [5,6,7,8,9,10]. Although all of these robotic platforms are designed for the purpose of legged locomotion, there are a few different approaches. One class of locomotion mechanism makes use of prismatic actuation in the legs. In this approach, a prismatic actuator pushes off the body when it touches down the ground [5,6]. In the second approach, robots recognize stance phases of a leg but without using prismatic actuation. The leg is controlled to set a particular angle during swing phase.

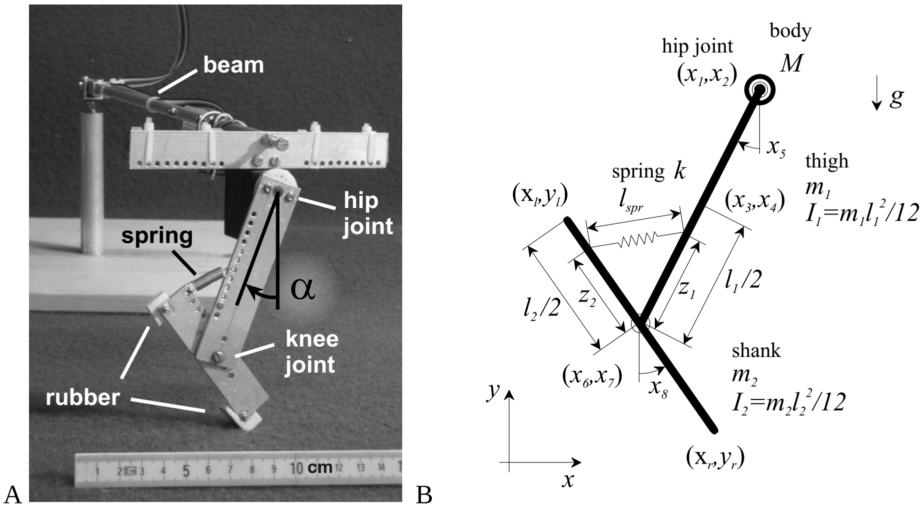

Figure 1. A: Fujubot, a one-legged robot with two segments and a compliant passive joint. A based beam holds the robots body. **B:** Schematic diagram of the simplified dynamic model used in simulations.

We aim to propose another class of legged locomotion with compliant legs, which uses no sensory information. Previously, it has been shown that, if the system has a good morphological properties such as spring stiffness and body dimension, it is able to achieve rapid four legged locomotion [8]. In this model, by simply swinging the legs back and forth, the system is able to achieve hopping locomotion behavior. Moreover, the system has to exploit the body dynamics derived from morphological properties, because there is no sensory information. For a better understanding of dynamic legged locomotion, we reduced the model to a single spring-like but also segmented leg that will be introduced in the next section. In this study, we investigate the characteristics of self-organized locomotion in relation to actuation and morphological properties in which we use a physical robotic platform and a simulation model. The performance criterions speed and actuator torques will be analyzed in detail to prove the behaviors in one-legged locomotion.

2. Methods

2.1. Mechanical application

The mechanical application (Fujubot) we used in this investigation is a one-legged robot with two segments shown in Figure 1A. The robot is approximately 15 cm in height and has a total weight of about 0.2 kg including additional masses behind the horizontal bar. Only one digital servomotor is implemented as actuator. This motor actuates the hip joint that is connected to the thigh segment (90 mm). A centered shank segment (80 mm) is connected to the thigh via a passive knee joint. In addition, the shank is elastically linked with the thigh by a spring. The spring stiffness k is 0.2 N/mm with a rest length of 25 mm. The rest angle of the knee joint is circa 130°. Therefore, the leg length is approximately 12 cm. Two elements of rubber at both ends of shank segment serve as damper when hitting the ground.

As shown in the background of Figure 1A, the body of Fujubot is held by a beam (0.34 m) and a base. This mounting, similar to Raiberts tether mechanism [5], constrains the motion of robots body leaving just two degrees of freedom. It moves forward and backward and up and down. Indeed, this robot is built imperfectly, hence, the mentioned retaining application has play in the joints. Especially the pitch axis has a play of up to $\pm 5\,^\circ$. Nevertheless, with the help of this mounting the robot does not need to be stabilized. Moreover, we are able to investigate the behavior of a segmented spring-like leg without using difficult control strategies.

2.2. Motor control

The hip actuator is realized by a position controlled motor. In experiments we used a simple sine oscillation as angular position signal.

$$\alpha(t) = \frac{\omega_{max}}{2\,\pi\,f}\,\sin\left(2\,\pi\,f\,t\right) + \alpha_0 \tag{1}$$

The maximum angular velocity ω_{max} was held constant at $360\,^\circ$/s and is a motor specific property. Furthermore, we are able to use the frequency f and offset angle α_0 as independent control parameters. In the experiments the frequency varied from 1.5 to 8 Hz in steps of 0.5 Hz, where the offset angle ran the gamut from $-25\,^\circ$ to $+25\,^\circ$ in increments of $5\,^\circ$. We have to notice that the maximum controllable position of the used motor averages at $\pm\,64\,^\circ$. Therefore, we limited the amplitude of the position signal at $38\,^\circ$ for frequencies lower than 3 Hz. According to [8], this control strategy does not need global sensory feedback.

2.3. Experimental method

In the experiments the robot moved in a circle on a flat ground surface. For kinematic analysis of the robots behavior and locomotion we attached reflective markers on the application. A high-speed (240 Hz) camera system (Qualisys) with six motion capture units recorded the three-dimensional coordinates of the markers. For data analysis we converted the measured trajectories into a two-dimensional plane.

2.4. Simulation model

In this study we also used a simplified simulation model as illustrated in Figure 1B. It has 4 degrees of freedom: the body coordinates x_1 and x_2 and the angular displacement of thigh and shank: x_5 and x_8. We replaced the equation of motion for x_5 while using kinematical control. The control was the same as discussed in the 2.2 except of the limitation of the amplitude at lower frequencies.

The ground is modelled as nonlinear spring and damper in vertical direction [11]. For horizontal direction, our ground reaction model is more complex. Here, we implemented a state machine for describing sliding friction and adhesive force when the foot stands still. It switches from sliding to sticking when the velocity of the foot becomes lower than a specified threshold. It switches back when the horizontal force becomes higher

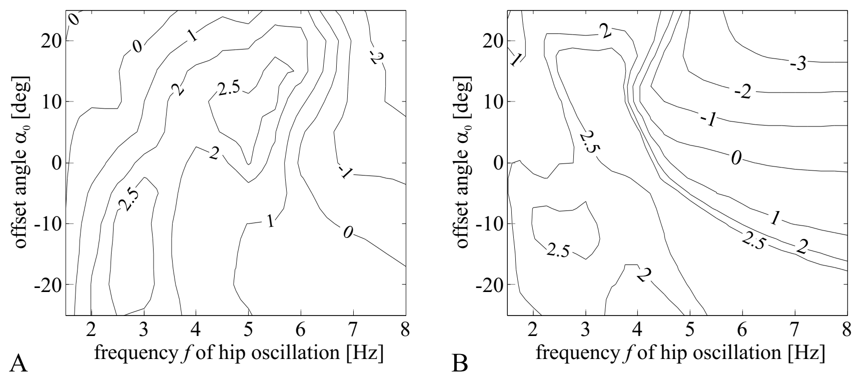

Figure 2. Average speed in horizontal direction of the robot (**A**) and the simulation model (**B**). The velocity is measured in leg lengths per second, whereas the leg is 12 cm in length.

than the force of sliding friction. See appendix for a detailed description of the ground model.

A difference of this model to the real existing leg is that this model has no play in the joints. We simulated this model using Matlab® 7.01 with additional toolboxes Simulink® and SimMechanics.

3. Results

Locomotion behavior of the two-segmented leg explained in the previous section is tested and analyzed by using the robotic platform and the simulation model.

First, we explore the relation between locomotion behavior and the control parameters, offset angle α_0 and the frequency of hip oscillation f. With every set of these two parameters, we conduct experiments for 30 seconds. We repeat the experiments two times and record the kinematic data of the robot by using the motion tracking system mentioned in section 2.3. By varying these parameters, we observe four clearly distinguishable patterns of locomotion, i.e. forward locomotion with one and two ground contacts, hopping at place and backward locomotion.

Figure 3B shows typical forward locomotion of this robot in which the robot touches down with the right end of lower segment. The spring is extended due to the ground reaction force. Because the robot efficiently uses the spring, this behavior generally results in faster locomotion. Another type of locomotion behavior shows ground contacts of both ends of the lower segment as shown in Figure 3A. Generally, after the right point touches down, the left end of the segment also hits the ground which results in slower but more stable locomotion behavior. This type of behavior is, however, mostly dependent on the parameter of offset angle as shown in Figure 3E. The backward locomotion shown in Figure 3C hardly uses the passive joint, which leads to unstable speed as explained later in this section. This behavior results in fast locomotion, but rarely.

In order to understand underlying mechanisms of these behaviors, we investigate locomotion speed with respect to the control parameters as shown in Figure 2A. For this analysis, we split the two-dimensional trajectories into cycles defined by motor oscilla-

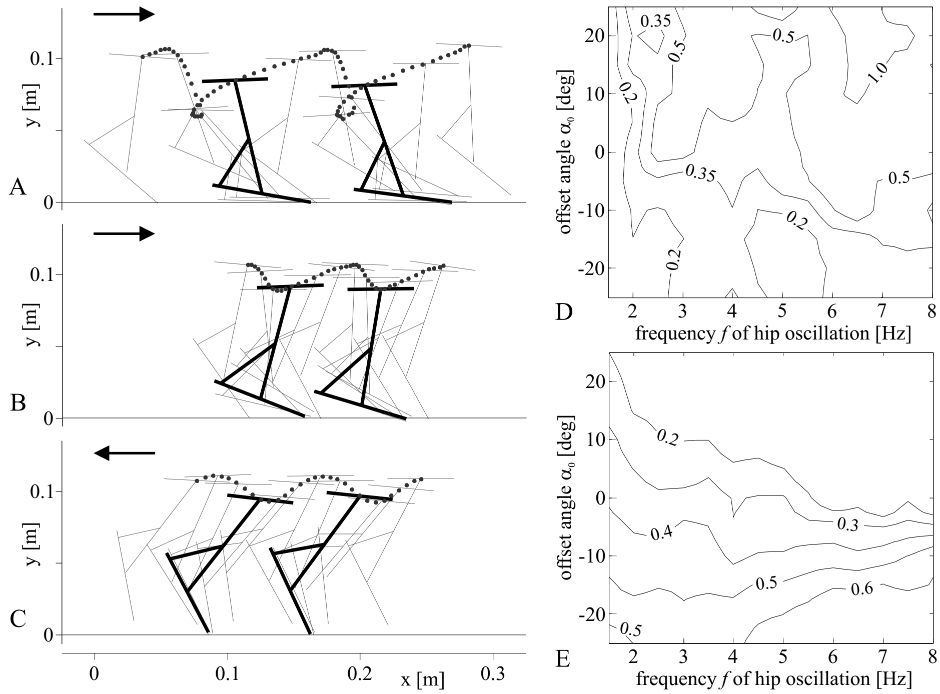

Figure 3. A-C: The stick figures shows two cycles of robots locomotion behavior. The direction of movement is described by the arrows. Parameters of motor control: **A:** $f = 3$ Hz, $\alpha_0 = -15\,°$, **B:** $f = 5$ Hz and $\alpha_0 = 10\,°$ and **C:** $f = 7.5$ Hz, $\alpha_0 = 25\,°$. The landscape in **D** illustrates the standard deviation of the robots horizontal velocity measured in leg lengths per second. In figure **E**, the length of time is shown where the left foot-point touches the ground in addition to the right foot-point. The values are normalized to cycle time of motor oscillation.

tion. For every set of parameters, offset angle and frequency, we randomly selected 120 movement cycles. The average speed of each cycle was calculated and we averaged it again. It is clearly shown that there are three peaks of speed in the landscape of control parameters, i.e. one peak in the lower frequency and lower offset angle, one in the middle, and the negative peak at the higher frequency and high offset angle. These peaks are corresponding to the forward locomotion with two ground contacts, the normal forward and the backward locomotion.

We conduct simulation experiments in the same manner, and it results in a similar perspective as shown in Figure 2B. Here, the limit where direction of hopping changes is displaced into lower frequencies. In contrast, the region of lower offset angles, where high speed locomotion is observed, spreads out to higher frequencies. These differences could be caused by the non-existence of compliance or play in the hip joint of the model.

For further characterization of the locomotion behavior we explored the periodicity of the cyclic motion. The periodicity is analyzed using standard deviation of average speeds of each motion cycle as shown in Figure 3D. The deviation was calculated by using the previous locomotion speed data. In this analysis, the standard deviation is to interpret as opposite value to periodicity. This means, low deviation in speed of the motion cycles describes high periodicity and vice versa. The figure shows that more periodic lo-

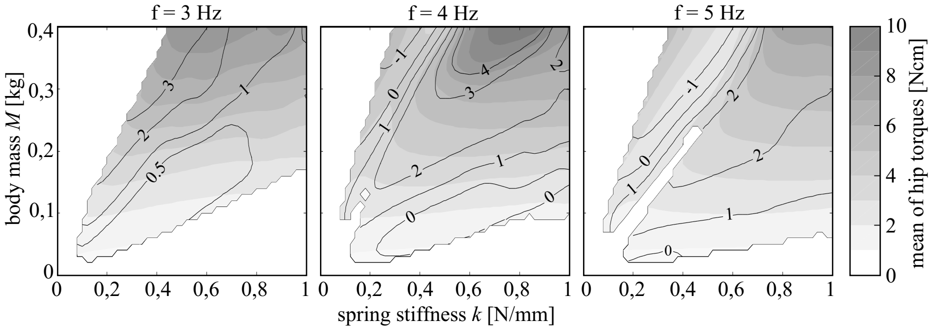

Figure 4. Simulation results: Absolute values of averaged hip torques during stance phase. The contour lines illustrate the forward velocity as additional performance criterion. The velocity is measured in leg lengths per second. The offset angle α_0 is held constant at $10\,^\circ$. Cleared regions indicate that the foot does not leave the ground.

comotion can be achieved with lower offset angles, and it becomes more unstable as the offset is increased. By considering the locomotion speed shown in Figure 2A, the best performance can be achieved by locomotion with two points in ground contact. Another region of higher performance is shown around the frequency of 5 Hz and an offset angle of approximately $10\,^\circ$. Here, a higher speed and a local minimum in deviation of speed was achieved where the robot shows normal forward locomotion.

So far, we have investigated the influence of control on morphology of hopping behavior. An additional analysis of the locomotion performance is explored in simulation with respect to the spring stiffness k and the body mass M. Here, we investigated the effects of these mechanical properties on the torque in the hip joint and again on speed as illustrated in figure 4. Both issues provide information about energy efficiency of locomotion. We calculated the torque by using the ground reaction forces during stance in conjunction to the leg vector. The data were averaged over 10 locomotion cycles in which the simulated leg was in steady state of hopping. The figure shows that with higher mass the torque mostly increases and therefore the raised energy increases too. Indeed, there is a linear connection between body mass and stiffness that causes in higher velocities if the legs natural oscillation frequency is considered. Furthermore, we observe that with low mass, i.e. 0.2 kg, the behavior is more independent on the stiffness but the speed is lower. Therefor, an exact adjustment of spring stiffness is not essential for achieving locomotion with compliant legs.

4. Conclusion

This paper presented preliminary experimental results of a single legged locomotion by using a robotic platform and simulation. Despite its simplicity, this locomotion model shows a few implications which are potentially important for our better understanding of dynamic locomotion behavior.

Even though this model is still attached to a supporting beam to prevent rotational movement of the body, the locomotion behavior is simply achieved without the necessity of sensory feedback. This is possible mainly because the system can self-stabilize

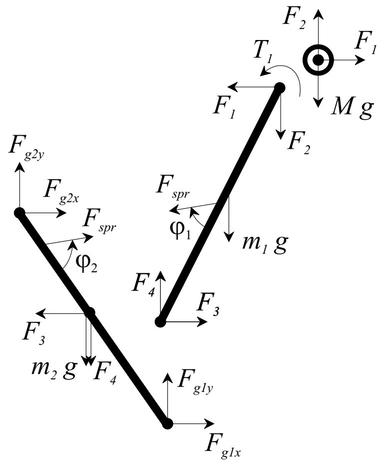

Figure 5. Dynamics of the two-segmented leg.

itself into a stable periodic movement by exploiting the body dynamics derived from mechanical properties and the ground interaction with the environment. In particular, it is important to note that morphological properties (e.g. body mass and spring stiffness) are the important design parameters in order to make this locomotion possible. One of the direct applications of this approach could be four (or more) legged locomotion as shown in some of the previous work [6,8,9]. Although the relation of the proposed locomotion model and the control of rotational movement has to be investigated further in the future. The minimalistic model explored in this paper provides further insights of self-stabilizing character in the processes of locomotion in general.

Appendix

Here, we introduce the ground reaction model in detail. The ground reaction forces $F_{g..}$ are exemplarily given for the right foot-point described as (x_r, y_r). All variables correspond to Figure 1A and Figure 5.

$$F_{g1y} = \begin{cases} -p_1 \left|\frac{y_r}{l_0}\right|^{e_1} \left(\mathrm{sgn}(y_r) + p_2 \left(\frac{\dot{x}_r}{\sqrt{g\, l_0}}\right)^{e_2}\right) \cdot m_t\, g & \text{for } y_r < 0, \\ 0 & \text{otherwise,} \end{cases}$$

$$F_{g1x} = \begin{cases} -p_1 \left|\frac{\Delta x_r}{l_0}\right|^{e_1} & \\ \cdot \left(\mathrm{sgn}(\Delta x_r) + p_3 \left(\frac{\dot{x}_r}{\sqrt{g\, l_0}}\right)^{e_2}\right) \cdot m_t\, g & \text{for } y_r < 0, \text{and so long as} \\ & F_{g1x} - \mu_1 F_{g1y} > 0 \\ -\mathrm{sgn}\,(\dot{x}_r)\, \mu_2 F_{g1y} & \text{for } y_r < 0, \text{and so long as} \\ & |\dot{x}_r| - v_{lim} > 0 \\ 0 & \text{otherwise,} \end{cases}$$

$$\Delta x_r = x_r - x_{r0} \qquad m_t = M + m_1 + m_2$$

The moment the state machine for describing horizontal ground reaction forces changes into adhesive friction, the horizontal displacement x_r is saved as reference x_{r0}. In our simulations we used the following constants:

$g = 9.81\,\mathrm{m\,s^{-2}}$	$M = 0.2\,\mathrm{kg}$	$m_1 = 0.01\,\mathrm{kg}$	$m_2 = 0.01\,\mathrm{kg}$
$l_0 = 120\,\mathrm{mm}$	$\mu_1 = 0.40$	$\mu_2 = 0.45$	$p_1 = 2.5 \cdot 10^5$
$p_2 = 3$	$p_3 = 1$	$e_1 = 3$	$e_2 = 1$
$v_{lim} = 0.01\,\mathrm{m\,s^{-1}}$			

Acknowledgements

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