Simulation study of a galloping quadruped robot with a flexible shoulder hammock structure

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1 Introduction

Quadrupeds have obtained an asymmetrical body shape along the cephalocaudal (head–to–tail) direction through evolution; this has helped them achieve adaptive and efficient locomotion. For example, cursorial quadrupeds, such as cats and horses, have different connectivities to the trunk between the fore and hindlimbs. The hindlimbs connect to the pelvis through deep ball-and-socket joints, and these secure connections can efficiently translate the reaction force from the ground to the entire body. In contrast, forelimbs connect to the chest through several muscles, and these flexible connections allow the quadruped to immediately adapt to changes in the environment. Understanding the functionality of these asymmetrical morphologies can aid in the establishment of a new robot design that differs from modern-day quadruped robots [1].

Biological studies have measured the flexibility of quadruped forelimbs during various tasks. Carrier et al. elucidated that the shoulder region muscles allow a dog to conserve the forelimb's motion despite various perturbations, for example, additional body weights, external forces, and ground level inclinations [2]. Zhang et al. measured the landing of cats from elevated places and showed that their forelimbs play an essential role in absorbing the impact at the landing moment [3]. Although the aforementioned studies suggest that the flexibility of the shoulder region contributes to the adaptive locomotion of the cursorial quadruped, it is challenging to extract useful anatomical characteristics owing to the complexity of the quadruped's musculoskeletal system.

To understand the functionality of a quadruped's forelimbs, we developed a simple robot model inspired by the flexible connections in proximal joints. The developed robot showed that the flexibility in the forelimb's base reduced the mechanical load upon landing from an elevated location [4]. Furthermore, the robot in the simulation demonstrated that the passive translational motion of the forelimb base reconciles the conflicts between the fore and hindlimb motions through the trunk, resulting in efficient walking [5]. We also conducted simulation experiments to assess the contribution of the robot's flexible shoulder during a galloping gait, which has a typical asymmetrical running pattern.

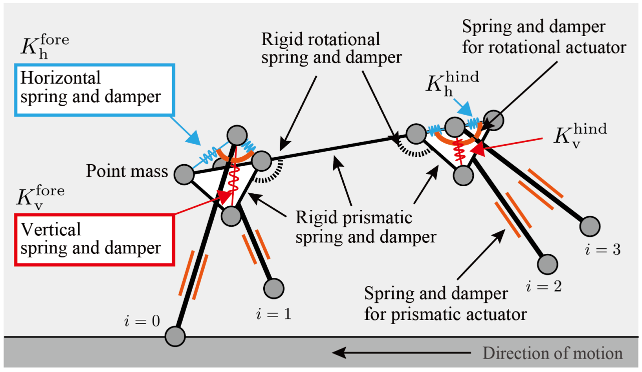

Figure 1: Mass-spring-damper system of a quadruped robot with a hammock structure

2 Model

In the shoulder of the cursorial quadruped robot, the forelimbs sling up the chest through the use of several muscles to support the body weight, similar to a hammock; this robot therefore has a shoulder hammock structure. For example, the ventral serratus muscles sling up the trunk from the forelimb's basement, that is, the scapula. Furthermore, the trapezius muscle modulate the horizontal motion of the forelimbs in response to perturbations. These flexible connections in the shoulder allow the forelimb base to move rotationally and translationally in the sagittal plane [6].

Based on the anatomical structure of the proximal joints of quadrupeds, a simple quadruped robot model is herein proposed as a mass-spring-damper system in the sagittal plane (Fig.1). The robot consists of a rigid trunk, two forelimbs, and two hindlimbs. Each limb connects with the trunk through a hammock structure using vertical and horizontal springss and dampers connect the limb's base and trunk. The base of the limb can move passively in the sagittal plane. By changing the spring and damper coefficients, $K_{\mathrm{v(h)}}^{\mathrm{fore(hind)}}$ and $D_{\mathrm{v(h)}}^{\mathrm{fore(hind)}}$, the limb base can realize flexible and rigid connections, such as those in the shoulder and hip regions of quadrupeds. Here, the indexes fore and hind represent the fore and hind limbs. The indexes v and h, represent the spring and damper located along the vertical and horizontal directions, respectively.

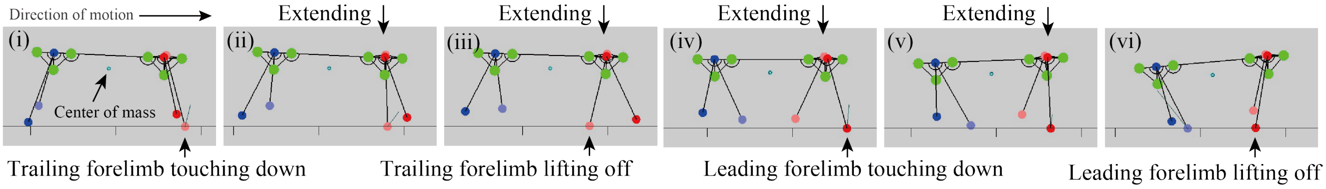

Figure 2: Deformation of the forelimb's base of the galloping quadruped robot with a flexible shoulder hammock structure.

In this study, the galloping motion of a robot with intra and inter-limb coordination was designed. Regarding intralimb coordination, a rotary actuator in the shoulder(hip) joint and a prismatic actuator in the ith limb coordinate such that the limb under consideration could follow a specific foot trajectory, which was an ellipse. Here, the index i identifies the limbs: $i = 0, 1$ for forelimbs and $i = 2, 3$ for hindlimbs. To generate the running patterns of the galloping gait, interlimb coordination with phase differences between the limbs was designed. The details of the model involving the interaction between the robot and the ground are described in a previous study [5].

3 Simulation

To evaluate the effects of the flexible shoulder, a running simulation of the robot with a galloping gait was conducted. To realize the galloping gait, a specific phase difference was set between the limbs: $\phi_1 - \phi_0 = 0.3$, $\phi_2 - \phi_0 = 0.5$, $\phi_3 - \phi_0 = 0.8$, where the phase of the ith limb described one stride motion from 0.0 to 1.0. The locomotor frequency was set at 2.3 [Hz]. To realize a flexible connection in the shoulder and a rigid connection in the hip, a low spring constant was set for the forelimb base ($K_\mathrm{v}^\mathrm{fore} = K_\mathrm{h}^\mathrm{fore} = 10^{2.6}$), and a high spring constant was set for the hindlimb base ($K_\mathrm{v}^\mathrm{hind} = K_\mathrm{h}^\mathrm{hind} = 10^{5.6}$). The other parameters were set heuristically.

The running robot showed different behaviors of the flexible shoulder during the stance phase of the trailing forelimb (the first touchdown forelimb) and the leading forelimb (the second touchdown forelimb). The base of the forelimb showed a large deformation during the trailing forelimb's stance phase and a smaller deformation during the stance phase of the leading forelimb (Fig.2). This was because the height of the chest was lower during the stance phase of the trailing forelimb than that of the leading forelimb during the same phase(Fig.3), and a large ground reaction force (GRF) was observed with the trailing forelimb. In contrast, the bases of the hindlimbs did not exhibit any deformations due to the rigid proximal connection, and a larger gap in the GRF occurred in the hindlimbs than in the forelimbs. These results suggest that the flexible connection in the forelimbs may reduce the load discrepancy due to the asymmetrical ground contact.

4 Conclusion and future work

In this study, multiple simulations of the galloping of a quadruped robot with a flexible shoulder hammock structure were conducted. The results suggested that the flexibility in the shoulder region may reconcile the differences in the load between the trailing and leading forelimbs in the case of asymmetrical quadruped running.

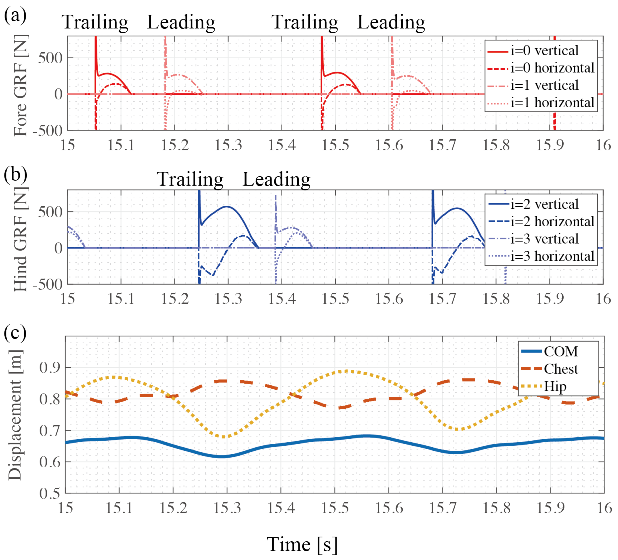

Figure 3: Ground reaction force of (a) forelimbs and (b) hindlimbs. (c) Vertical displacement of the body parts and the center of mass(COM).

For future studies, the effect of asymmetrical and symmetrical stiffness properties on the shoulder and hip joints will be evaluated in various real world locomotor tasks, such as, walking, running, and jumping by using a developed robot [4]. In addition, a control mechanism will be developed to adjust the stiffness of the shoulder according to the physical condition of the robot.

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References

[1] Boston Dynamics. Introducing spot (previously spotmini). `https://www.youtube.com/watch?v=tf7IEVTDjng&feature=youtu.be`, 2016. Accessed: 2021-02-24.

[2] D.R. Carrier, S.M. Deban, and T. Fischbein. Locomotor function of the pectoral girdlemuscular sling'in trotting dogs. *Journal of Experimental Biology*, 209(11):2224–2237, 2006.

[3] Z.Q. Zhang, H. Yu, J.L. Yang, L.L. Wang, and L.M. Yang. How cat lands: insights into contribution of the forelimbs and hindlimbs to attenuating impact force. *Chinese Science Bulletin*, 59(26):3325–3332, 2014.

[4] A. Fukuhara, Y. Masuda, M. Gunji, K. Tadakuma, and A. Ishiguro. Development of quadruped robot that can exploit shoulder hammock structure. In *2020 IEEE/SICE International Symposium on System Integration (SII)*, pages 1139–1143. IEEE, 2020.

[5] A. Fukuhara, M. Gunji, Y. Masuda, K. Tadakuma, and A. Ishiguro. A bio–inspired quadruped robot exploiting flexible shoulder for stable and efficient walking. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 7832–7839, 2020.

[6] A.W. English. Functional analysis of the shoulder girdle of cats during locomotion. *J Morphol*, 156(2):279–92, 1978.