On the role of the leading limb in quadrupedal turning

Tomoe Maeta[1,2], Hayato Amaike[1,2], Akira Fukuhara[1], Takeshi Kano[1], Akio Ishiguro[1]
[1]Research Institute of Electrical Communication, Tohoku University, Sendai, Miyagi, Japan
[2]Graduate School of Biomedical Engineering, Tohoku University, Sendai, Miyagi, Japan
maeta.tomoe.r7@dc.tohoku.ac.jp
a.fukuhara@riec.tohoku.ac.jp

1 Introduction

Frequent and rapid directional changes are crucial for quadrupeds exposed to predator-prey relationships. Preys evade by frequently altering their direction when being pursued by predators. Predators also adjust their direction in response to the maneuvers of the prey [1]. A comprehensive understanding of the mechanisms that underlie directional changes at such high speeds would not only contribute to the understanding of the biology of quadrupeds, but also aid in the development of legged robots that can perform rapid changes in direction.

Many quadrupedal mammals use a four-beat asymmetric gait called gallop to move at the highest speed. Interestingly, the galloping quadrupeds exhibit a specific limb coordination of the forelimb pair along the direction of turning(Fig. 1(a)) [2]. The external forelimb first touches the ground (trailing limb), followed by the internal forelimb (leading limb). The pattern of forelimb coordination according to the direction of turning is commonly observed in various galloping patterns, such as transverse and rotary galloping [3]. In addition, the "lead change" is the transition between the footfall sequences of the right and left leads (Fig. 1(b)), which occurs when the direction of movement is changed [4].

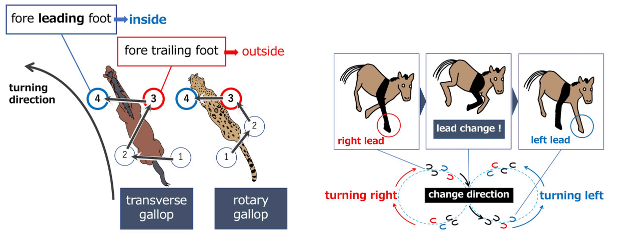
Despite the findings of the "lead change" phenomenon, the underlying control mechanisms remain unexplored. Smith et al. developed a quadruped robot with no external sensors and demonstrated that the robot rotated in an asymmetric gait with a rotary gallop [5]. However, the mechanism that causes the directional change remains unclear.

This study aims to present a better understanding of the control mechanism of adaptive lead changes and directional turns. As an initial step, we developed a simulation platform and validated our hypothesis. The hypothesis is that the quadrupeds automatically turn in the direction of the leading foot without any presumed directive from a higher level in the asymmetric gait similar to the gallop. As a result, when the lead change was made with no feedback, the direction was changed to the side with the leading limb.

2 Model

2.1 Mechanical system

Figure 2 illustrates the overall configuration of the model, which consists of four legs with an identical structure



(a) (b)

Figure 1: Behavior of quadrupeds in turning. (a) Both horses and cheetahs use the internal forefoot as a lead when turning in a canter or gallop. (b) "Lead change" indicates switching the leading foot from left to right.

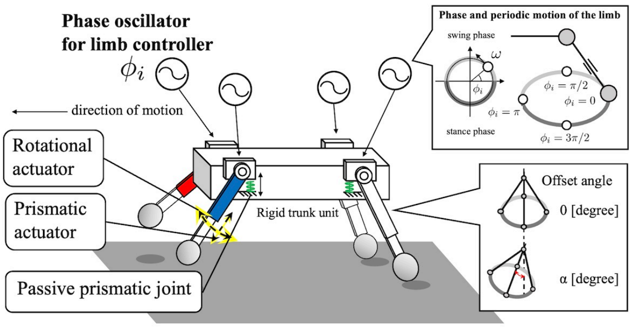


Figure 2: Schematic of the model.

and a rigid trunk without degrees of freedom. The model was assumed to be a small mammal with a body length of 0.35 m, leg length of 0.21 m, and a total mass of 2 kg. Each limb has two actuators: one prismatic actuator at the knee joint and one rotary actuator at the hip joint. A passive spring was positioned between the limb basis and trunk.

2.2 Control system

Each limb has a phase oscillator; the phase of oscillator ϕ_i describes the periodic stride motion of the ith limb（i=LF: left forelimb, RF: right forelimb, LH: left hindlimb, RH: right hindlimb）(Fig.2). The time evolution of the oscillator phases at the ith leg are described as follows:

$$\dot{\phi}_i = \begin{cases} \omega_{swing} & (\text{if} \quad 0 \le \phi_i < \pi), \\ \omega_{stance} & (\text{if} \quad \pi \le \phi_i < 2\pi), \end{cases} \tag{1}$$

where ω_{swing} and ω_{stance} are positive values in the swing and stance phases, respectively. The target angle of the hip joint

$\bar{\theta}_i$ and the target length of the knee joint $\bar{L}_i$ are described as follows:

$$\bar{\theta}_i = \theta_i^{offset} + \theta^{amp}\sin\phi_i, \quad (2)$$

$$\bar{L}_i = L^{offset} + L^{amp}\cos\phi_i, \quad (3)$$

where θ_i^{offset} and θ^{amp} are the offset angles of the trajectory and amplitude angle, respectively. L^{offset} and L^{amp} are the offset and amplitude length, respectively.

The phase relationship between each foot was established assuming that the left and right feet of both the front and rear pairs were in phase. Furthermore, the phase difference between the front and rear pairs was determined based on the observed behavior of actual animals.

2.3 Gait pattern

We used a symmetrical bound gait as a basis, where the left and right limbs were in phase, instead of a transverse or rotary gallop. Subsequently, we examined the effect of implementing left-right asymmetry in the phase or trajectory of the forelimbs upon movement.

In this study, we assumed a symmetrical phase relationship between the left and right limbs and introduced asymmetry in the leg movement. Specifically, we set different trajectories by providing varying offset angles for the right forelimb (RF) and left forelimb (LF), considering the following two control modes: left-lead and right-lead. For the left-lead mode, we set the offset angles as (θ_{LF}^{offset}, θ_{RF}^{offset}) = (θ^{lead}, θ^{trail}). θ^{lead}, θ^{trail} are the offset angles intended for the leading and trailing feet, respectively. In contrast, for the right-lead mode, we set the offset angles as (θ_{LF}^{offset}, θ_{RF}^{offset}) = (θ^{trail}, θ^{lead}). As θ^{lead} is greater than θ^{trail}, the leading limb extends farther forward than the trailing limb. In both modes, the hindlimbs are set to the same offset angle, that is, $\theta_{RH} = \theta_{LH} = \theta^{hind}$. In this study, θ^{lead}, θ^{trail}, and θ^{hind} were set as 15.0, 0.49, and -15.0 degrees, respectively.

3 Result

This study aims to investigate the effect of the leading limb on the direction of turning. We conducted a 3D simulation using the open dynamics engine [6]. First, we created a bound gait without feedback by fixing the initial phase. We then created a half-bound gait by separating the forelimbs into the leading and trailing limbs; the left- and right-lead modes were switched periodically.

Figure 3 demonstrates where the offset angle of the forelimbs alternates between left and right over time. The direction of movement turns toward the leading limb, resulting in a trajectory resembling a slalom.

4 Conclusion

In this study, we created a platform as the first step toward understanding the control mechanism of the leading limb and turning. We observed that during a half-bound gait with the leading limb created by changing the offset angle of the forelimbs, the movement turns toward the leading limb. In the future, we plan to investigate why the movement turns toward the leading limb and verify the conditions under which the lead change can be smoothly performed without crashing.

Figure 3: Trajectory of the center of mass of the robot trunk during the running simulation. Depending on changes in the offset angles θ_i^{offset}, the robot changes the direction of motion between left and right.

5 Acknowledgement

This research was partially supported by the JSPS Grant-in-Aid for Scientific Research (B) [grant number JP21H01269 and JP22H01429].

References

[1] A.M. Wilson, T.Y. Hubel, S.D. Wilshin, et al. "Biomechanics of predator–prey arms race in lion, zebra, cheetah and impala." Nature, 554(7691):183– 188, 2018.

[2] M.Hildebrand. "The mechanics of horse legs." American Scientist, 75(6):594–601, 1987.

[3] H. Ichikawa, T. Matsuo, M. Haiya, et al. "Gait characteristics of cheetahs (acinonyx jubatus) and greyhounds (canis lupus familiaris) running on curves." Mammal study, 43(3):199–206, 2018.

[4] W. Back and H. M. Clayton. "Equine locomotion." Elsevier Health Sciences, 2013.

[5] J. A. Smith and I. Poulakakis. "Rotary gallop in the untethered quadrupedal robot scout II." In 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)(IEEE Cat. No. 04CH37566), 3:2556–2561, IEEE, 2004.

[6] R. Smith. "Open dynamics engine", 2007.