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A galloping quadruped model using left–right asymmetry in touchdown angles

Masayasu Tanase [a], Yuichi Ambe [a], Shinya Aoi [b,c,*], Fumitoshi Matsuno [a]

[a] Department of Mechanical Engineering and Science, Graduate School of Engineering, Kyoto University, Kyoto Daigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan
[b] Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Kyoto Daigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan
[c] JST, CREST, 5 Sanbancho, Chiyoda-ku, Tokyo 102-0075, Japan

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ABSTRACT

Among quadrupedal gaits, the galloping gait has specific characteristics in terms of locomotor behavior. In particular, it shows a left–right asymmetry in gait parameters such as touchdown angle and the relative phase of limb movements. In addition, asymmetric gait parameters show a characteristic dependence on locomotion speed. There are two types of galloping gaits in quadruped animals: the transverse gallop, often observed in horses; and the rotary gallop, often observed in dogs and cheetahs. These two gaits have different footfall sequences. Although these specific characteristics in quadrupedal galloping gaits have been observed and described in detail, the underlying mechanisms remain unclear. In this paper, we use a simple physical model with a rigid body and four massless springs and incorporate the left–right asymmetry of touchdown angles. Our simulation results show that our model produces stable galloping gaits for certain combinations of model parameters and explains these specific characteristics observed in the quadrupedal galloping gait. The results are then evaluated in comparison with the measured data of quadruped animals and the gait mechanisms are clarified from the viewpoint of dynamics, such as the roles of the left–right touchdown angle difference in the generation of galloping gaits and energy transfer during one gait cycle to produce two different galloping gaits.

1. Introduction

Quadruped animals use various gaits depending on the locomotion speed. They use a walking gait in the lowest range of locomotion speed, and this changes to a trotting gait as the locomotion speed increases. In the highest range of locomotion speed, they use a galloping gait. These gaits are characterized by footfall sequence (Muybridge, 1957). During gaits used at slow speeds, such as a walking gait, at least one limb is in contact with the ground, that is, in the stance phase. In contrast, gaits used at higher speeds, such as a galloping gait, have a flight phase during which all four limbs are in the air, that is, in the swing phase. These gaits have been investigated from mechanical, energetic, kinematic, and kinetic viewpoints to clarify the underlying mechanism for the use of such different gaits depending on the locomotion speed (Alexander and Jayes, 1983; Farley and Taylor, 1991; Hildebrand, 1977, 1989; Hoyt and Taylor, 1981; Minetti et al., 1999).

Among these quadrupedal gaits, the galloping gait has characteristic properties. Differing from the walking and trotting gaits, the galloping gait is asymmetric (Alexander and Jayes, 1983; Hildebrand, 1977, 1989). More specifically, the relative phase of the movements between the left and right limbs is away from the antiphase, unlike the walking and trotting gaits, as shown in Fig. 1A. In addition, as the locomotion speed increases, the relative phase decreases and approaches the in-phase as in a bounding gait, which is not generally used by large, cursorial quadrupeds (Marhefka et al., 2003). There are two types of galloping gaits in quadruped animals, the transverse gallop and the rotary gallop, and the two gaits have different footfall sequences (Fig. 1B) (Hildebrand, 1977). The transverse gallop is the preferred gait of horses, and the foot contacts take place in the order of a hindlimb, the contralateral hindlimb, the ipsilateral forelimb, and the contralateral forelimb. The rotary gallop is the preferred gait of dogs and cheetahs, and the foot contacts occur in the sequence of a hindlimb, the contralateral hindlimb, the contralateral forelimb, and the ipsilateral forelimb. Both gallops have a flight phase after the liftoff of the forelimbs. In contrast, the fast rotary gallop of

* Corresponding author at: Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University, Kyoto Daigaku-Katsura, Nishikyo-ku, Kyoto 615-8540, Japan.
E-mail address: shinya_aoi@kuaero.kyoto-u.ac.jp (S. Aoi).

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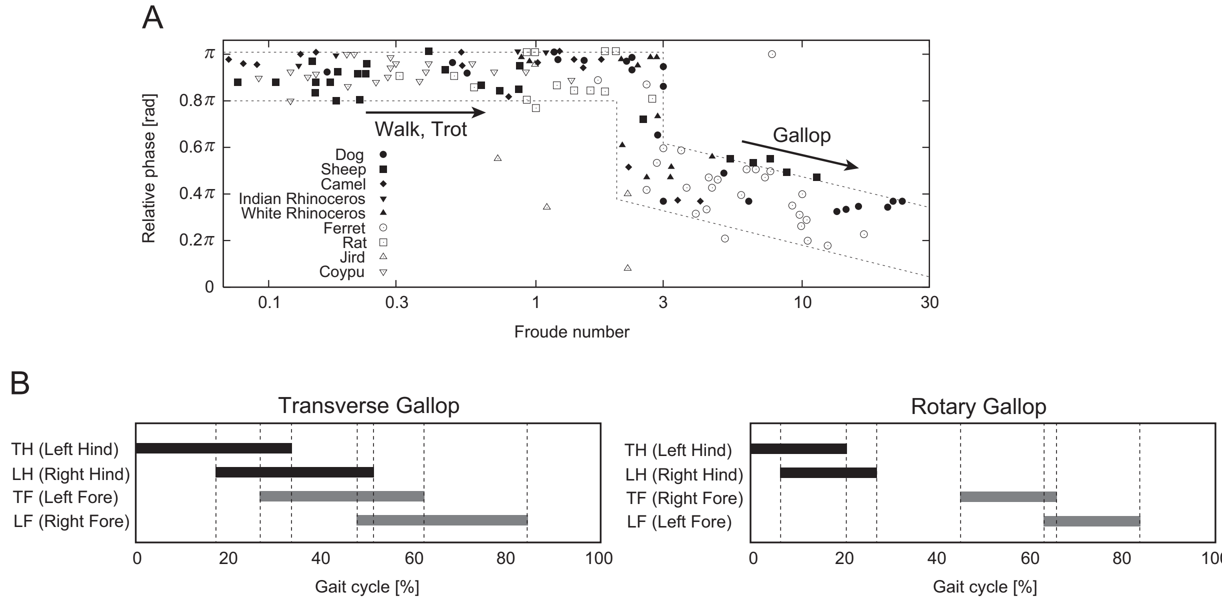

Fig. 1. Characteristics of the quadrupedal galloping gait. (A) Relative phase between left and right forelimbs of quadrupeds depending on locomotion speed (Froude number), modified from Alexander and Jayes (1983). Although it remains almost antiphase in the walking and trotting gaits, it is away from the antiphase and approaches the in-phase in the galloping gait as the locomotion speed increases. (B) Footfall diagrams of the transverse gallop of horses and the rotary gallop of dogs and cheetahs, modified from Hildebrand (1977). The transverse gallop has a single flight phase after the liftoff of the forelimbs, while the rotary gallop has two flight phases after the liftoff of the hindlimbs and forelimbs. TH: trailing hindlimb, TF: trailing forelimb, LH: leading hindlimb, and LF: leading forelimb.

dogs and cheetahs has another flight phase after the liftoff of the hindlimbs, unlike the transverse gallop of horses (Biancardi and Minetti, 2012; Hildebrand, 1989) (some species show a rotary gallop with just one flight phase at low speeds (Hudson et al., 2012)). Although these specific characteristics in quadrupedal galloping gaits and the dependence on the locomotion speed and species have been observed and described in detail (Alexander and Jayes, 1983; Biancardi and Minetti, 2012; Hildebrand, 1977, 1989), the underlying dynamic mechanisms remain unclear.

Locomotion in humans and animals involves moving the center of mass (COM) of the whole body using the limbs. The essential contribution of a limb in locomotion dynamics can be represented by a spring. To explain the locomotion mechanisms from a dynamic viewpoint, spring-loaded inverted pendulum models have been used (Blickhan, 1989; Bullimore and Burn, 2006a,b, 2007; Cavagna et al., 1977; Full and Koditschek, 1999; McMahon and Cheng, 1990; Minetti, 1998; Raibert, 1986). In particular, for human running, the dependence of stability on touchdown angles has been clarified (Geyer et al., 2005; Ghigliazza et al., 2003; Seyfarth et al., 2002). A simple model having mass and two springs has been used to explain the characteristic difference between human walking and running, which appears in the vertical ground reaction forces: a double-peaked shape in human walking, and a single-peaked shape in human running (Geyer et al., 2006). For quadrupedal locomotion, a rigid body with two springy legs has shown the stability characteristics of a bounding gait (Cao and Poulakakis, 2013; Poulakakis et al., 2006). The difference in the energy levels between the trotting, bounding, and galloping gaits also has been examined (Nanua and Waldron, 1995). Although simple physical models with leg springs have been used for the quadrupedal galloping gait (Herr and McMahon, 2001; Marhefka et al., 2003; McMahon, 1985; Nanua and Waldron, 1995; Waldron et al., 2009), they do not explain the above-mentioned specific characteristics. In this paper, we use a simple physical model with a rigid body and four massless springs. The simulation results show that our model produces stable galloping gaits for certain combinations of model parameters, and explains these specific characteristics in the quadrupedal galloping gait. The results are then evaluated in comparison with quadruped animals and the gait mechanisms are discussed from the viewpoint of dynamics.

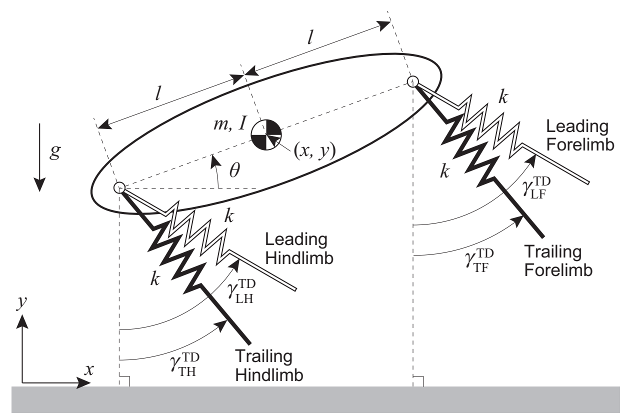

Fig. 2. Physical model of galloping consisting of a rigid body and four massless springs in two dimensions.

2. Materials and methods

2.1. Physical model

In this paper we use a physical model, which consists of a rigid body and four massless springs in two dimensions (Fig. 2), as used in Nanua and Waldron (1995). x and y are, respectively, the horizontal and vertical positions of the COM of the body, and θ is the pitch angle. m and I are, respectively, the mass and moment of inertia around the COM. l is the distance between the COM and the root of the spring. g is the gravitational acceleration. $+x$ is the locomotion direction. The front two springs and the rear two springs represent the forelimbs and hindlimbs, respectively. The spring constant is k. In the forelimbs, the anterior limb during the swing phase is the leading forelimb (LF) and the posterior limb is the trailing forelimb (TF). Similarly, the anterior and posterior hindlimbs during the swing phase are the leading hindlimb (LH) and trailing hindlimb (TH), respectively.

During the swing phase, the spring length remains the neutral length l_0 and the angle relative to the vertical line keeps the specific value γ_i^{TD} (i=LF, TF, LH, TH), which corresponds to the touchdown angle ($\gamma_{LF}^{TD} \geq \gamma_{TF}^{TD}$, $\gamma_{LH}^{TD} \geq \gamma_{TH}^{TD}$). We assumed $\gamma_{LF}^{TD} + \gamma_{TF}^{TD} \geq 0$ and $\gamma_{LH}^{TD} + \gamma_{TH}^{TD} \geq 0$ so that the trailing limbs contact the ground earlier than the leading limbs, as observed in quadruped animals. When a spring tip