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The Role of Relative Spinal Motion during Feline Galloping for Speed Performance

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Abstract

Felines use their spinal column to increase their running speed at rapid locomotion performance. However, its motion profile behavior during fast gait locomotion has little attention. The goal of this study is to examine the relative spinal motion profile during two different galloping gait speeds. To understand this dynamic behavior trend, a dynamic motion of the feline animal (Felis catus domestica) was measured and analyzed by motion capture devices. Based on the experiments at two different galloping gaits, we observed a significant increase in speed (from 3.2 m·s^{-1} to 4.33 m·s^{-1}) during the relative motion profile synchronization between the spinal (range: 118.86˚ to 168.00˚) and pelvic segments (range: 46.35˚ to 91.13˚) during the hindlimb stance phase (time interval: 0.495 s to 0.600 s). Based on this discovery, the relative angular speed profile was applied to understand the possibility that the role of the relative motion match during high speed locomotion generates bigger ground reaction force.

Keywords: feline galloping, galloping gait pattern, relative spinal motion, speed performance, phase match

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1 Introduction

Much insight and improvement in robotic locomotion has been achieved by the observation, study, and mimicking of animals. The increased speed of legged robotic systems is one factor that can benefit from a “bio-inspired” robotic design. Among quadruped animals, felines such as the cheetah are the fastest and attain speeds of up to 104.4 km·hr^{-1}[1]. Significant increases in speed may therefore result from the observation and study of feline anatomical design and patterns of locomotion.

Bio-inspired research for increasing the speed of legged robots was firstly focused on the sequence in which legs make contact with the ground. In terms of the static gait terminology, the main idea is directly related to the Center of Gravity (CoG) of the support pattern created by the contact of legs with the ground[2–4]. Research has then been conducted into various gait patterns with the change in speed based on the animal gait references. In terms of a low speed gait pattern such as a “trot”, the quadruped animal generates the leg contact as diagonal pairs simultaneously[5]. As the locomotive speed of quadruped mammals increases, the legs are synchronized in the front-rear and lateral directions, for example, during “pace” or “bound.” At maximum running speed (called a “gallop”), each leg of a quadruped mammal makes contact with the ground separately[6]. Based solely on these patterns of sequential ground contact, many quadruped robotic systems have been developed[7–13].

In addition to the sequence of leg-ground contact, another very important characteristic of high speed quadruped movement is the dynamics of the spinal column. Despite the importance of the spinal movement, the relation between spinal movement and the speed performance have not been studied in detail. Previous research showed that in terms of the energy consumption perspective, low speed generation can be satisfied using only the legs within a permitted energy consumption range. However, at high speed such as galloping, the quadruped animal changes its behavioral posture with the combination of the spinal and leg actuation to maintain similar power consumption of the trot gait[14].

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In view of the speed perspective, the usage of the spinal column is to increase the contact time and force with the ground during a gallop, thereby storing additional potential energy[15,16]. Release of the stored energy during spinal straightening allows an increased stride length[17,18] and extra power[19].

To explain such benefits of the spinal motion, many dynamic models have been applied to the system. At the early stages of the research, Raibert firstly analyzed the relationship between the body and leg segments as a symmetric behavior expressed by even and odd functions[20]. Concerning fast running locomotion, Spring-Loaded Inverted Pendulum (SLIP) model was introduced especially for the transition from the flexion to the extension phase of the body system. With this model, the prediction of the self-stabilization and attack angle for the extension was analyzed by Lagrangian dynamics formula[19–22]. In view of the relationship between the body structure and galloping as rigid links, Deng *et al*. proposed a quadruped system model consisting of two equal rigid rods connected by an elastic spinal joint[25].

Few attempts have been made to incorporate the merits of spinal movement into a robot platform. In the controller perspective, Leeser and Culha proposed a controller followed by Raibert's laws for a planar quadruped robot system with a spinal joint at a bounding gait[26,27]. Folkertsma *et al.* applied parallel stiffness to the spinal joint of a running quadruped robot called MITCheetah, decreasing the power consumption during high speed running[28]. For fast quadruped systems, Boston Dynamics CHEETAH first showed the possibility of the fast gait performance with pelvic movement in a tethered boom environment[29]. A recent quadruped platform (Wildcat) performed the bound and galloping gaits with the spinal movement in a field environment[30].

However, little has been revealed about the relationship between speed increase by the legs and the spinal motion in high speed locomotion. Although the transition between flexion flight to hindlimb stance is known to generate the speed increase by leg sequence[31], the role of the spinal movement of a domestic cat in a galloping gait has yet to be explained in view of the external contact during the transition phase between the hindlimb stance to the extension flight phase for maximum bending[32].

While taking into consideration an analysis of the gait sequences with respect to speed, this study investigates the role of the relative spinal motion in enhancing the running speed. In section **2**, measurement of feline galloping gait is introduced. For the experimental range set, the threshold value of the galloping gait was around 2.5 $m\cdot s^{-1}$–3.0 $m\cdot s^{-1}$[33,34]. Based on this value, 20 experimental results are sorted out with two different speeds range called low (2.5 $m\cdot s^{-1}$ – 3.5 $m\cdot s^{-1}$) and high (3.0 $m\cdot s^{-1}$– 4.5 $m\cdot s^{-1}$) speed galloping.

We analyze relevance between the relative spinal and pelvic motion match depending on two different gait speeds, low and high speed galloping in section **3**. Based on the analysis, section **4** concludes the paper.

2 Experimental procedure

We set an experimental environment for examining the relative motions of the spine and pelvis of a domestic cat (Felis catus domestica). At a low speed gait such as trot, speed is generated by the symmetrical cross leg contact. In contrast, in the galloping gait, the forelimb contacts the ground first and is followed by hindlimb contact with the ground during acceleration[35]. During this sequence in high speed gait, the spinal movement is applied to the body trunk. To investigate these gait sequences, the dynamic behavior of the spinal and pelvic movement is observed at two different galloping gait speeds. To study the gait sequences, we performed a set of motion experiments using a high speed camera and motion capture device for data acquisition.

2.1 Maker placement on an experimental object for the dynamic behavioral experiment

As shown in Figs. 1 and 2, and Table 1, ten points on a vertical planar cross-section of the experimental object, (felis catus domestica, 1 year old, weight : 2.54 kg, male, size 650 mm × 325 mm × 130 mm), were selected to monitor changes in the patterns of body movement. As shown in Fig. 1 and Table 1, four markers designated F_1 to F_4 were placed in order on the joints of the four bones in the forelimb structure. Similarly, four markers, H_1 to H_4, were placed on the hindlimb structure.

Due to the difficulties in precisely identifying points on the lumbar and thoracic vertebral columns, two points corresponding to the spinal column on the body trunk of the domestic cat were designated as markers