

Interaction between motions of the trunk and the limbs and the angle of attack during synchronous gaits of the pika (*Ochotona rufescens*)

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Abstract

We analysed the trajectory of the body center of mass (CoM) of the pika during half–bound gaits redundantly using high–speed kinematics and integration of ground reaction forces. The relative motion of the CoM in the body is mainly determined by the bending and extension of the back. In relation to the forelimbs the CoM is aligned with the ulna of the trailing or the leading limb during the major part of the forelimbs' stance phase. The angle of attack is rather speed–independent in half–bound. Additionally we could observe a distinct handedness of trailing and leading limbs.

1. Introduction

Synchronous gaits, where the feet within a pair of fore– or hindlimbs touch ground with only slight time differences, gain growing interest in robotics. In comparison to the machines using symmetrical gaits (where feet are placed in diagonals – on the definition of gaits cf. [1],[2]) programming work is hoped to be simplified considerably by stronger coupling of DOFs. In extreme the Buehler hopper shows a pure bound, with no phase difference occurring within a pair of legs.

Animals are as well able to produce pure bounds (e. g. Bouncing artiodactyls like goats even move all four legs synchronously), but the common synchronous locomotor mode of small (and thus the ancestral) mammals is the half–bound. The hindlimbs are moved synchronously, while the forelimbs show fluctuating phase lags. The leg which touches the ground first is called „trailing forelimb“, the other one which shows the greater cranial excursion thus is called the „leading limb“ [3].

Material

We performed our analyses in this study with the pika (*Ochotona rufescens*: Lagomorpha), a small tailless mammal. It owns a body weight of 150–200 g, a crown–rump–length of 140 mm and a height of the CoM over ground 45 mm (for a picture of this animal cf. Witte et al., this issue). It lives in the steppes of central Asia. Its kinematic motion principles have been discovered by [4]. The half–bound is the gait currently used by the pika as it wants to escape rapidly (fig. 1).

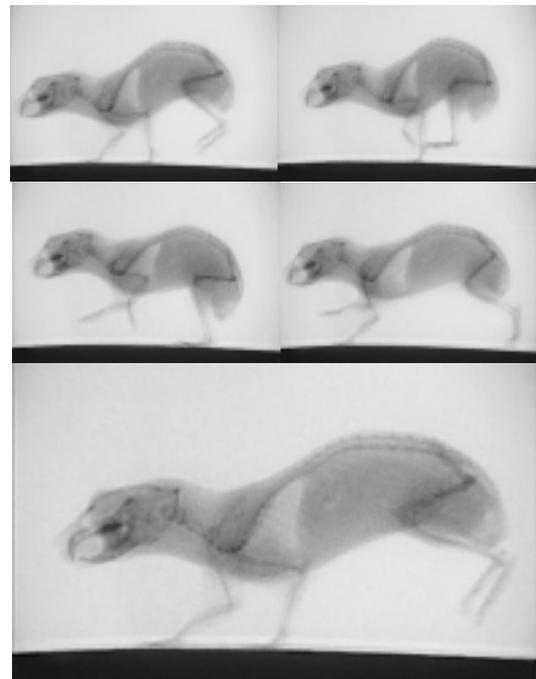


Figure 1: Pika (*Ochotona rufescens*) in half–bound. Cineradiography with 150 fps. Five events during one motion cycle in time intervals of 33 ms. The hindlimbs move synchronously, while the forelimb show a phase difference.

2. Handedness of the forelimbs during the pika's half-bound

Methods

Three pikas were filmed from the lateral side with one camera at a frequency of 1.000 fps, half-bounding on a treadmill at different speeds distributed in the following intervals [1.0;1.4[(slow), [1.4;1.8[(medium) and [1.8;2.2] (fast).

Results

Pikas show a preference in the choice of their trailing forelimbs (fig. 2). With increasing speed this preference becomes more evident.

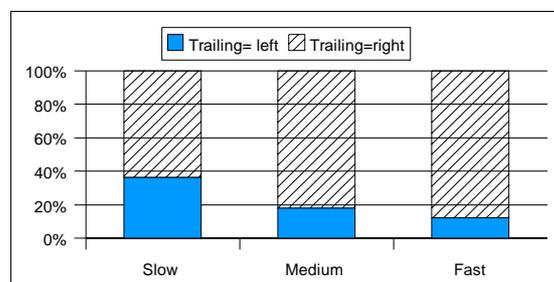


Figure 2: The individuals under study prefer one body side for the first touch down in a motion cycle of half-bound (trailing forelimb). Example for the frequency of side-different ground contact of one individual (N=517 step cycles) to illustrate the distinct handedness.

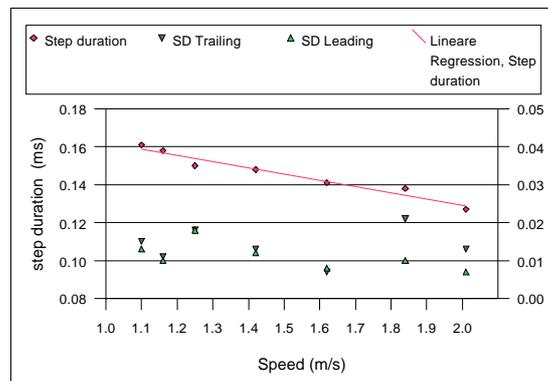


Figure 3: Step duration of the pika in half-bound. At speeds > 1.8 m/s, the SD (standard deviation) of the step duration is significantly higher ($p < 0.05$) for the leading limb than for the trailing limb. SD have to be read on the right scala. At each speed N = 20 motion cycles were analysed.

The step duration of a pika is described by a decreasing power like function of speed [4]. In half-bound, this function may be linearized (fig. 3). At high speeds ($v > 1.8$ m/s), in the three individuals under study we noted that the standard

deviation of the cycle duration of the leading limb to the next touch down was significantly smaller than the standard deviation of the cycle duration of the trailing limb ($p < 0.05$).

These two observations may reflect a functional difference of the two forelimbs and initially motivated the following study on the side-different analysis of the interaction of the limbs with the trunk. At first, we were interested in the time-variant location of the CoM to precise its position relatively to the limbs, and to discover whether we could observe any effects of „handedness” (which means kinematic asymmetry) on the guidance of the CoM.

3. The motion of the CoM in the body during half-bound

Methods

We filmed a pika as described in §2 running on the treadmill at a speed of 2m/s. This speed turned out to be the mean velocity of the pikas as they were escaping from unexpected dangers along our runway over a force plate. A second camera documented the front view, to ensure that the pika was running straight forward (the treadmill belt is twice as wide as the pika). At this speed, the step frequency is about 8 cycles per second. To control the permanence of speed, the lateral zoom-camera was adjusted in the way that the picture just covered the length of the pika as it was extended.

At a frequency of 1.000 fps the high speed cameras (Camsys®, optics: zoom Fujinon® 2.0/12.5–75.5 mm) provide a resolution of 256 x 64 pixels. To control the effects of optical distortion, a reference grid (mesh width 10 ± 0.05 mm, steel balls of 1 ± 0.01 mm diameter) was filmed and served as a control for linearization means. The contour of the body was digitised in the global frame with 35 points alternately distributed on the ventral and dorsal border of the sagittal projection of the animal. The limb segments were incorporated into the body shape proximally of the elbow and knee joints. 90% of the animal mass is included in this digitised area.

The distribution of the points on the body outline defined a series of triangles, the areas and centers of which were computed from the corner coordinates. To take account of the mass distribution, we weighed a series of 14 transversal slices of a pika frozen in its extended position (fig. 4).

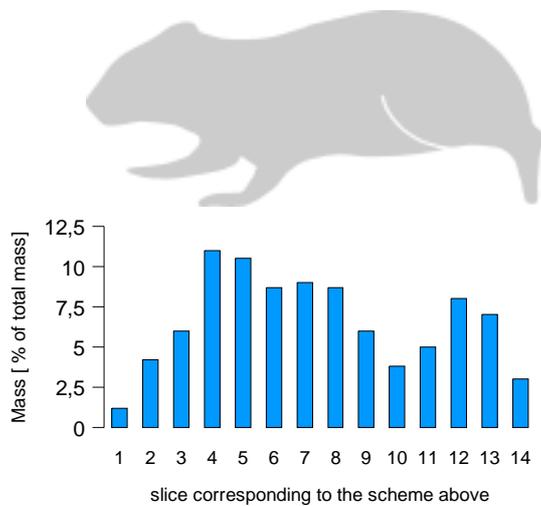


Figure 4: Mass distribution of the trunk of a Pika (*Ochotona rufescens*) including the upper arm (proximally of the elbow joint) and the thigh.

These values were the basis for the computational weight distribution onto the triangles. We thus implicitly neglected the effect of oscillating masses, or seen the other way round, since the thickness of the zone defined by the base of the triangle is about 1cm, this means that the masses have been considered to oscillate locally in this volume.

Results

Motion of the center of mass in the body:

- The above described method leads to motion patterns which are comparable to the pattern issued from the two-fold integration of ground reaction forces.
- The CoM is located just underneath the lung base. It is closer to the ventral outline than to the dorsal one (40:60) (fig. 5).
- The relative position of the CoM relatively to the nose (which is a representative for the rather unaccelerated head) is not constant (fig. 6). The horizontal excursion of the CoM is in fixed phase coupling with the motion of the back. During spinal extension, which takes place during the stance phase of the hindlimbs, and at the beginning of the forelimbs' stance phase the CoM moves caudal. During spinal bending the CoM moves cranial. This excursion equals about 15 % of the animals' length (fig. 7)
- The amplitude of the vertical motion relative to the nose is about 10 mm (fig. 6).

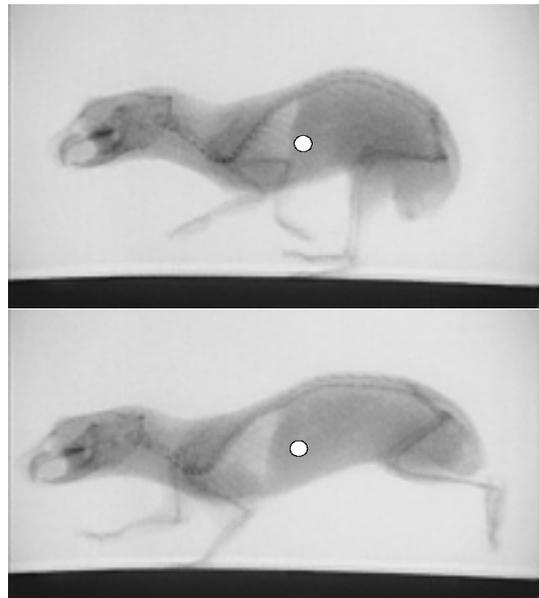


Figure 5: Location of the CoM during half-bound of a pika. For means of comparability, for this illustration the same cineradiographic pictures have been taken as in Witte et al., fig. 4 [this issue].

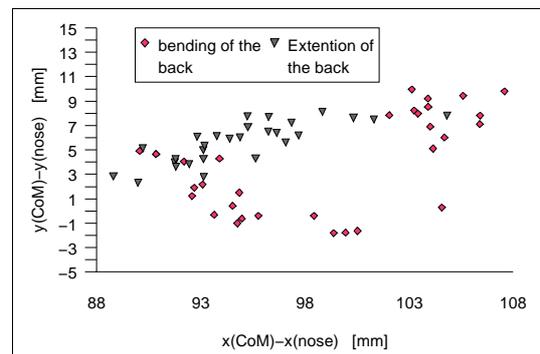


Figure 6: Motions of the CoM relative to the nose during half-bound of a pika.

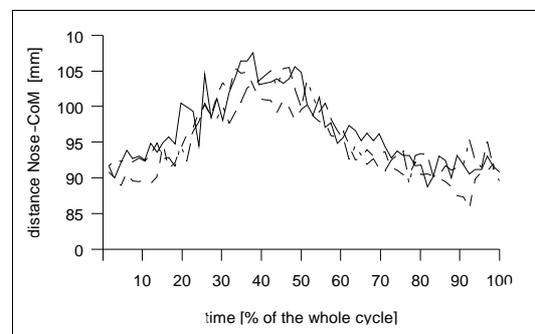


Figure 7: Horizontal distance between the CoM and the nose during the half-bound of a pika for three steps serie. Footfall pattern are shown fig. 8.

Vertical motions of the CoM in the global frame:

- The amplitude of the motion of the CoM at 2 m/s accounts for about 6 mm (10% of the animal height of about 60 mm (fig. 8)).
- The extension phase of the back is dominated by a downward movement of the CoM with a possible ascent at the end. In the flexion phase of the back after initial descent the CoM moves upward (fig. 8).
- The global vertical motion pattern may have one or two local extrema.

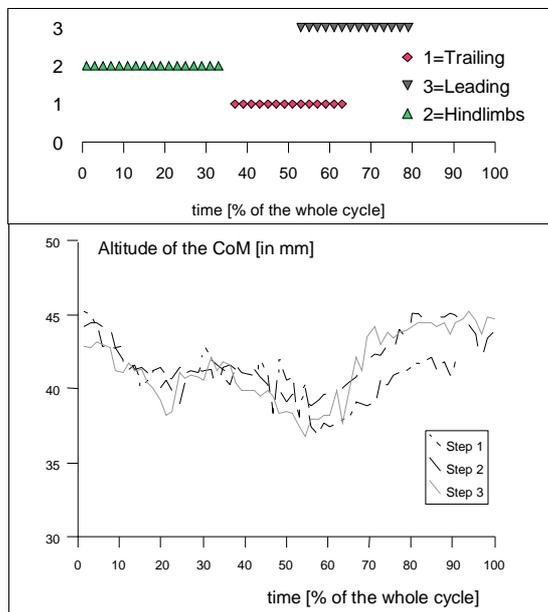


Figure 8: Vertical excursions of the CoM during half-bound of a pika and above the corresponding footfall pattern.

Position of the CoM relative to the forelimbs:

- The angle wrist–elbow–CoM of the trailing forelimb is about 180° during that part of its stance phase when no other ground contacts occur (fig. 10).
- After the leading forelimbs touches the ground, the weight is transferred to it: the alignment CoM–trailing ulna decreases while the alignment with the leading ulna becomes almost complete (fig. 10).

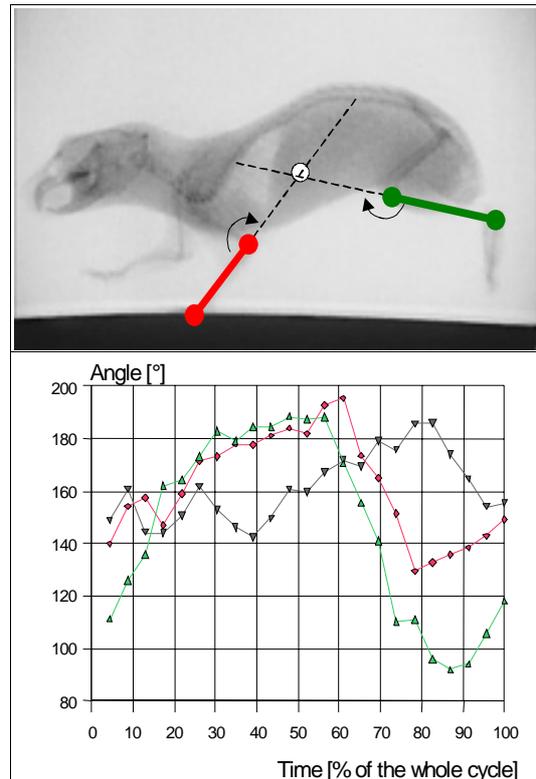


Figure 10: The angle wrist–elbow–CoM of the trailing forelimb is about 180° during that part of its stance phase when no other ground contacts exist. During late mid stance the leading forelimb takes over and its ulna points to the CoM. Alignment of the shank (kinematically equivalent to the upper arm) mainly occurs during aerial phases. For the footfall pattern see fig 8.

4. Does the angle of attack couple with speed ?

The angle of attack is defined as the angle formed between the connection line of CoM and the ground contact point and the ground. To quantify the variation of the angle of attack with speed we take advantage of the above detailed experience that at touch down of the trailing limb the ulna points in the direction of the CoM. The orientation of the ulna does not coincide with the direction defined by the connection line of the ground contact point (underneath the metatarso–phalangeal joint) and the CoM. The error we provoke is a systematic error of $+5^\circ$.

Methods

The cineradiographic apparatus accessible to us provides 150 fps. This frame rate is insufficient to determine significant values for the angle of attack, since a pika may run up to 8 steps per second. Consecutively we shaved the forelimbs of a pika and filmed its half-bounding on the treadmill with the high speed video system (500 fps, resolution of 256x256 pixels).

The camera field was adjusted to cover one pika length. This enables a rigorous control of the pika speed.

Results

- The angle of attack does not strongly vary with increasing speed.
- The difference between the mean values are small but significant (t-Test $p < 0.10$ for the four first values).
- The angle ulna/ground equals 50° ; consequently the angle of attack is about 45° .

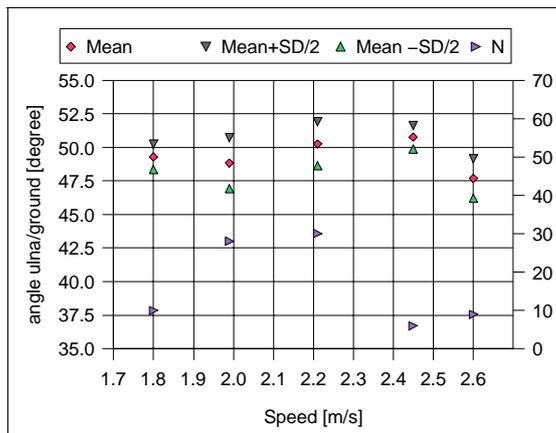


Fig 11. The variations of the angle ulna/ground with speed are small. The right scale gives the number of steps N used to calculate the mean values.

5. Discussion

The small mammal's limb is a four segmented flexed structure, which may be compared to a pantograph [5]. It effectively allows compensation of small irregularities of the ground and also plays the role of a spring-damper system as the pika runs or trots. The occurrence of elastic phenomena during legged locomotion is commonly accepted in biology (cf. [6], [7], [8] and succeeding publications). The movement of the human CoM

during running may be described using spring-mass models [9], [10]. The vertical excursion of the CoM of the half-bounding pika (about 7 mm) relatively to the leg length (70 mm) is quite comparable to the excursion of the CoM in human running (about 10 %) (cf. [11]). From this point of view (in addition to many others), it also seems promising to extend these templates to quadrupedal locomotion [12]. In humans the spring-leg and the mass (CoM) are well aligned. The above described results indicate, that the common linear spring-point mass model may well be applied to the situation in the pika's forelimbs. In the hindlimbs, the consideration of the mass extension of the trunk seems inevitable. [13] calculate how the angle of attack of a spring-mass system defined as the angle which minimized the maximum of the force during the stance phase vary as a function of the horizontal and vertical velocity. The variation of this angle with horizontal velocity was also small (about 7°).

6. Conclusion

Our study shows that the motion of the trunk is a determinant factor in the motion of the center of mass of a small mammal. The model of a rigid body that jumps from one limb to the other is not able to explain the variety of the pattern of the vertical motion of CoM by running locomotor modes. The bending of the back is not a passive bending due to the inertia of the back, since the deceleration in the forward direction by landing of the forelimbs is minimal (a few percent). For robotics the Raibert idea of minimizing dissipative energy flows in combination with the usage of intelligent, self-stabilising mechanics with minimal neuronal/computational control effort is attractive. The understanding of motion systems evolutionally tested for longer periods in this context may be a promising directive.

7. Acknowledgments

We thank Prof. R. Blickhan, who kindly provided us access to the high speed camera system. Dr. D. Haarhaus invested his experience in a multitude of cineradiographic experiments performed at the Institut fuer den wissenschaftlichen Film (IWF) in Goettingen, Germany.

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