Interactions between Motions of the Trunk and the Angle of Attack of the Forelimbs in Synchronous Gaits of the Pika (*Ochotona rufescens*)

Remi Hackert[1], Hartmut Witte[1,2] and Martin S. Fischer[1]

[1] Institut für Spezielle Zoologie und Evolutionsbiologie,
Friedrich-Schiller-Universität Jena, Erbertstraße 1, D-07743 Jena, Germany,
Remi.Hackert@animals-in-motion.com
[2] Fachgebiet Biomechatronik, Technische Universität Ilmenau, Pf 100565,
D-98684 Ilmenau, Hartmut.Witte@tu-ilmenau.de

Abstract. During half-bound gait on a treadmill pikas (*Ochotona rufescens*: Lagomorpha) show a preference in the choice of the trailing limb ("handedness"). Duration of steps shows significantly higher variation in the trailing limb than in the leading limb. This observation motivated calculations of the position of the center of mass (CoM) in the body frame of the pika during half-bound cycles. CoM is aligned with first of the ulna of the trailing and second of the leading limb during major parts of the forelimbs‘ stance phase. Referring to our large cineradiographic data base on the kinematics of the legs we could note that the horizontal motion of the CoM in the body is mainly determined by flexion and extension of the back. This observation underlines the determinant role of the trunk as the main engine for fast locomotion. Using high-speed video films we measured the angle of attack (defined as the angle between the ulna and the ground at touch down). We couldn't observe any significant change with speed during half-bound, indicating the important role of self-stabilising mechanisms on the choice of kinematics.

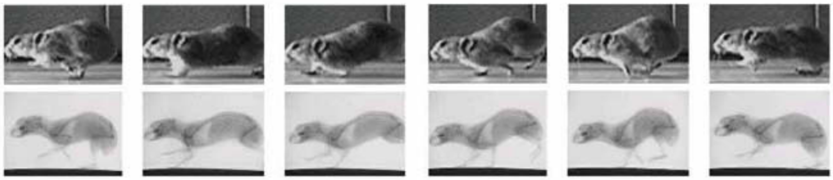

Fig. 1. Pika (Ochotona rufescens) in half-bound. Cineradiography with 150 fps. Six events during one motion cycle in time intervals of 25 ms are shown. The hindlimbs move synchronously, while the forelimb show a phase difference (leading vs. trailing limb). Please note especially the flexion of the spine.

1 Introduction

Synchronous gaits, where the feet within a pair of fore- or hindlimbs touch the 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 - definition of gaits cf. Hildebrand 1965, 1977), programming work is simplified considerably. In the extreme case, the Buehler hopper shows a pure "bound", with no phase difference within each pair of legs. Animals are as well able to produce a pure bound (e. g. "bouncing" goats), but the common synchronous locomotor mode of small (and ancestral) mammals is "half-bound". The hindlimbs are moved synchronously, while the forelimbs show a fluctuating phase lag. The leg which touches the ground first is called "trailing limb", the other one shows the greater cranial excursion and thus is called the (spatially) "leading limb" (fig. 1).

We performed analyses on four male pikas (Ochotona rufescens: Lagomorpha), small tailless mammals living in the steppes of central Asia. They own body weights of 150-200 g, crown-rump-lengths of 140 mm and heights of the CoM over ground of 45 mm. Kinematics have been described in detail in [4]. Pikas are performing half-bound at speeds between 1.2 m/s and 2.4 m/s.

2 Preliminiary question: do pikas prefer one forelimb as trailing limb?

We filmed the animals in lateral view with a high speed video system (Micromac® Camsys® + Zoom lenses Fujinon® 2,0/12.5-75.5 mm) at 500 Hz. The duration of each session accounted for about one hour. The pikas ran 30 seconds and were filmed 15 seconds at each sequenc followed by a recreation period of 3 minutes. Speed was staged between 1.2 m/s and 2.2 m/ with a step width of about 0.1 m/s. The effective treadmill speed was controlled via tracking the movements of markers disposed along the treadmill belt. The results of the experiment clearly indicate that pikas systematically prefer one of their forelimbs as the trailing one (fig. 2). With increasing speed this preference becomes more evident but the differences between medium and fast half-bound not always were significant.

The step duration of a pika is described by a decreasing power like function of speed (Fischer and Lehmann, 1998). In the range of half-bound speed, this function may be linearized (cf. fig. 3). At very high speeds (> 1.75 m/sec), in the individuals under study here we noted that the standard deviation of the step duration measured from touch-down of the leading limb to the next touch-down was significantly smaller than the standard deviation of the step duration measured for the trailing limb.

These results indicate that even in animals using their "hands" (fore feet) for running a handedness exists, which even in a small group of animals shows differences between individuals what concerns the preferred side. May this be an indicator of a body side specific specialization of the extremities (in mechanical performance and/or control), even without profound knowledge about the bases of this effect it indicates that “the” motion scheme of “the” pika does not exist – in so far pikas are real individuals.

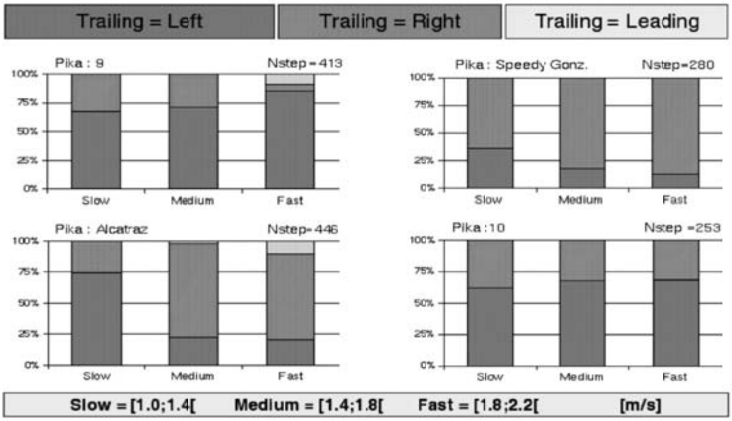

Fig. 2. The four individuals under study systematically preferred one of their forelimbs for the first touch down in a motion cycle of half-bound (trailing forelimb).

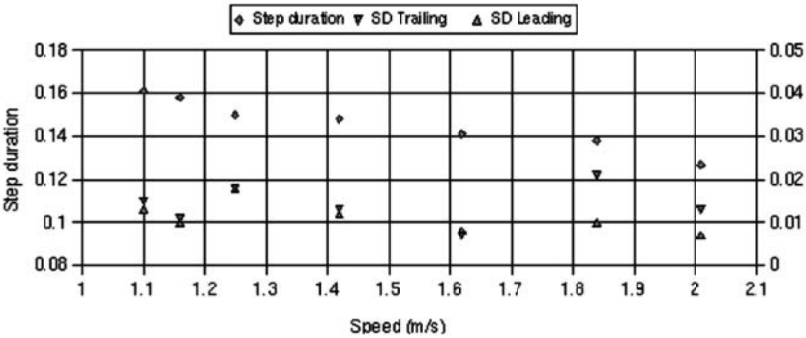

Fig. 3. Step duration of the pika (Ochotona rufescens) in half-bound. At speeds > 1.75 m/sec, the S.D. of the step duration is significantly higher ($p < 0.05$) for the leading limb than that for the trailing limb. At each speed n = 20 motion cycles were analysed.

3 Trajectories of the centre of mass of pikas in half-bound gait

3.1 Method: Videoradiography.

The animals were filmed at a frequency of 1,000 fps, half-bounding on a treadmill at a speed of 2.0 m/s. At this speed, the step frequency is about 8 cycles per second. At 1,000 fps the high speed cameras provide a resolution of 256 x 64 pixels. The treadmills belt is twice as wide as a pika's body width. One camera was used to film the pikas from the lateral side (the ground appears to be a line on the screen). To control the permanence of speed, this lateral zoom-camera was adjusted with the maximal focus length (75 mm) in such a way that the picture just covered the length of the animal when it was maximally extended. A second camera documented the front view, to ensure that the pika was running straight forward.

3.2 Method: Digitization

To control the effects of optical distorsion, a reference grid (mesh width 10 ± 0.05 mm, steel balls of 1 ± 0.01 mm in diameter) was filmed and served as a control for linearization means. The outline of the body was digitised in the global frame with 35 points alternately distributed on the dorsal and on the ventral border of the sagittal projection of the animal. Limb segments were incorporated into the body shape proximally of the elbow and knee joints. The background of the picture (grid of the Faraday‘s cage of our laboratory) was filled with vertical lines spaced approx. 1 cm. We took advantage from these lines to get an equal distribution of the digitisation points along the body contour. 90% of the animal's mass is included in this digitised area. The number of points used for digitising the body outline arose to be a good compromise between the needs for the binding line between two even following points to stay near to the contour line and the wish to limit the expense for the digitising work.

3.3 Method: Weighing of triangle segments of trunk elements

The distribution of the points on the body outline defined a series of triangles, the areas and centers of which were computed from their corner coordinates. To take account of the mass distribution, we weighed a series of 14 transversal slices of a pika cadaver frozen in its extended position (fig. 4). These values were the base for the computational weight distribution onto the triangles. We thus implicitely 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 1 cm, this means that the masses have been considered to oscillate locallly in this volume.

3.4 Results

Motion of the center of mass in the body:

- The CoM is located underneath the lung base. It is closer to the ventral outline than to the dorsal one (40:60) (fig. 4).
- The position of the center of mass relatively to the nose (which is a representative for the rather unaccelerated head) is not constant. 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 in the cranio-caudal direction. During spinal bending the CoM moves in the caudo-cranial direction. This excursion equals about 10 % of the animals' length (fig. 5).

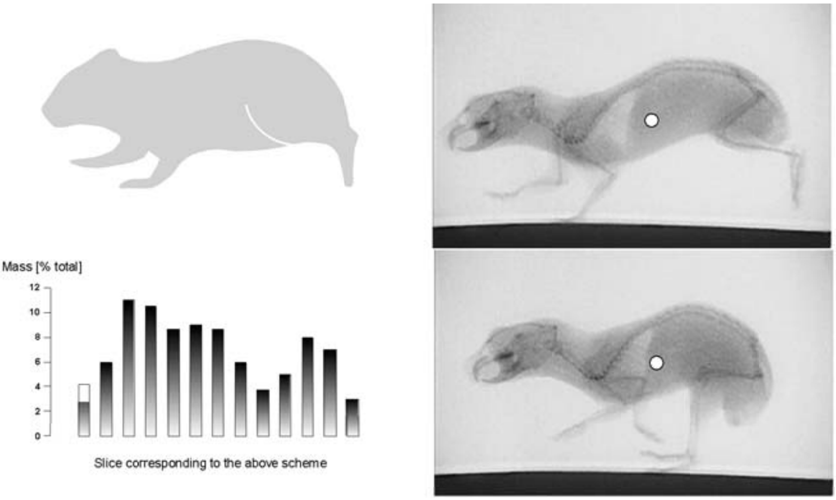

Fig. 4. Left: Mass distribution of the trunk of a pika (*Ochotona rufescens*) including the upper arm (proximally of the elbow joint) and the thigh. Right: position of the center of mass at touch down of the forelimbs (extended back) and of the hindlimbs (bended back). The radius of the circle corresponds to the strength of the interval of confidence.

Vertical motions of the CoM in the global frame:

- The amplitude of the motion of the CoM at 2 m/sec accounts for about 6 mm (10% of the animal's height) (fig. 5).
- During the extension of the back the CoM globally moves down, during the bending of the back it globally moves up (fig. 5).
- The pattern of the CoM vertical motion has more than two extrema.

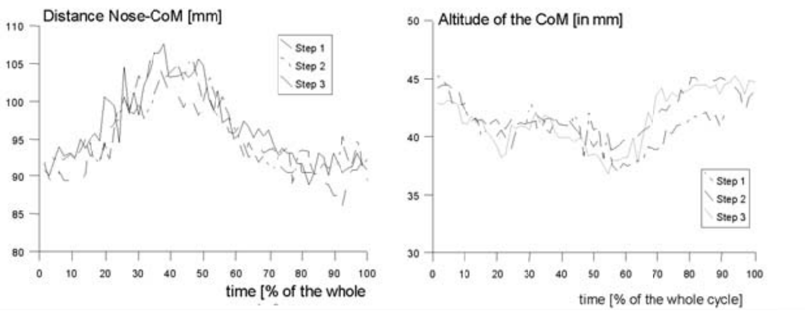

Fig. 5. Motions of the CoM during half-bound of a pika (*Ochotona rufescens*).
Left: horizontal excursions relative to the nose
Right: Vertical excursions with corresponding footfall patterns

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 exist (fig. 6).
- After the leading forelimb 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.

4 Does the angle of attack couple with speed?

The angle of attack is defined as the angle formed by the connection line of CoM and the ground contact point versus ground. To quantify the variation of the angle of attack with speed we took advantage of the above described effect that at touch down of the trailing limb the ulna points is in the direction of the CoM. The orientation of the ulna does not coincide exactly with the direction defined by the connection line of the ground contact point (underneath the metatarso-phalangial joint) and the CoM. This error is systematic and accounts for + 5°.

4.1 Methods

The high speed X-Ray camera accessible to us provided 150 fps. This frame rate is insufficient to determine significant values for the angle of attack, since a pika at observation speed may run up to 8 cycles per second. Consecutively we shaved the forelimbs of a pika and filmed the half-bounding animal 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 pika speed.

4.2 Results

1. The angle of attack does not variate strongly with increasing speed (fig.7).
2. The angle ulna/ground equals about 50 °, consecutively the angle of attack is about 45 °.

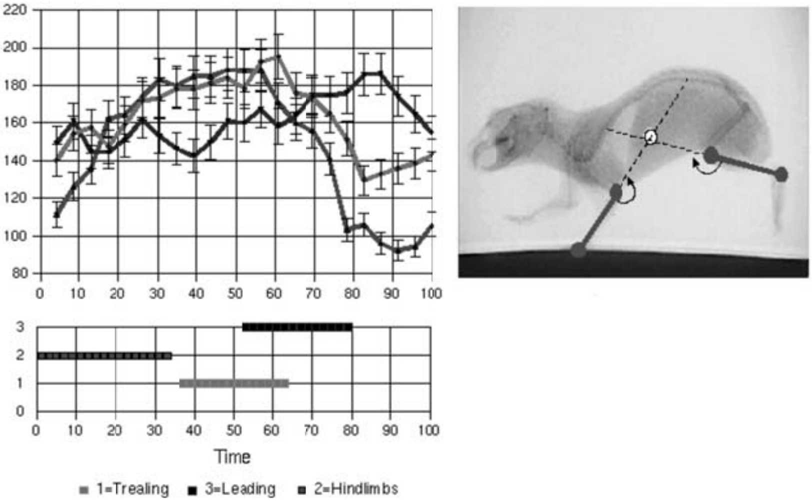

Fig. 6. The angle wrist-elbow-CoM of the trailing forelimb is about 180 ° during that part of its stance phase when no other ground contacts exist. During late mid stance the leading forelimb takes over and its ulna points to the CoM. Alignment of the shank (kinematically eqivalent to the upper arm) mainly occurs during aerial phases.

5 Conclusions

The small mammal's limb is a four segmented flexed structure, which may be compared to a pantograph [5]. It effectively allows for compensation of small irregularities of the ground. It also plays the role of a spring-damper system as the pika runs or trots. The occurance 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 a half-bounding pika (about 5-6 mm) relatively to the leg length (70 mm) is quite comparable to the excursion of the CoM in human running (about 10 %) [11]. From this point of view (in addition to many others), it also seems promising to extend these templates to quadrupedal locomotion

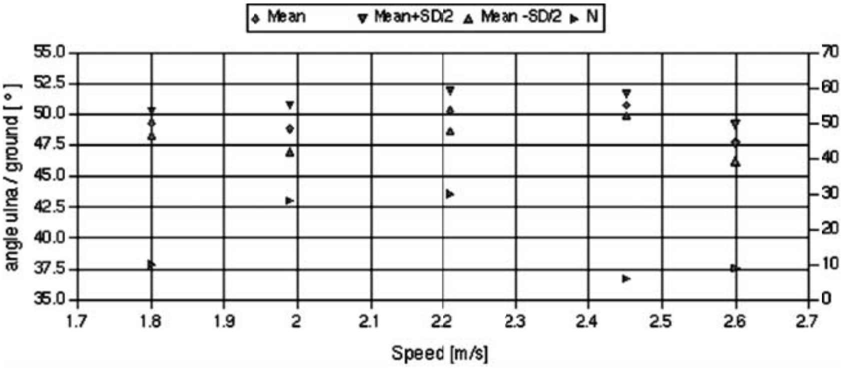

Fig. 7. Variations of the angle ulna/ground with speed are small. The right scale gives the number of steps N used to calculate the mean values and the standard deviations.

[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 as 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. The variation of the CoM height found in this study is very similar to that for the dog derived from numerical integration of ground reaction forces by Cavagna et al. [7]. In that case the vertical displacement of the CoM over time showed more than two extrema. McMahon & Cheng [13] calculated 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 variates as a function of the horizontal and vertical velocity. The variation of this angle with horizontal velocity also is small (about 7 °). The reasons for an almost constancy of this angle still are poorly understood as far as the dynamics of locomotion is concerned, but perhaps may find an explanation by the results of further studies on the dynamic stability of quadrupedal locomotion.

Our study shows that the motion of the trunk is a determinant factor in the motion of the CoM. 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 vertical motions of CoM provoked by running locomotor modes. Bending of the back is not a passive bending due to inertia of the back. 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. Understanding of motion systems evolutively tested for longer periods in this context may be a promising directive.

Acknowledgments

We thank Prof. R. Blickhan, who kindly provided us access to the high speed camera system. Dr. D. Haarhaus invested his ecxperience in a multitude of cineradiographic experiments.

References

1. Hildebrand M.(1965): Symmetrical gaits of horses. – *Science* 150: 701-708.
2. Hildebrand M.(1977): Analysis of asymmetrical gaits. – *J Mamm* 58(2): 131-156.
3. Jenkins F.A.(1971): Limb posture and locomotion in the Virginia opossum (*Didelphis marsupialis*) and other non-cursorial mammals. *J Zool (Lond)* 165: 303-315.
4. Fischer M.S. & Lehmann R.(1998): Application of cineradiography for the metric and kinematic study of in-phase gaits during locomotion of the pika (*Ochotona rufescens*, Mammalia: Lagomorpha). - *Zoology* 101: 12-37.
5. MS Fischer & H Witte (1998): The functional morphology of the three-segmented limb of mammals and its specialities in small and medium-sized mammals. *Proc Europ Mechanics Coll Euromech* 375 Biology and Technology of Walking: 10–17.
6. Cavagna G.A., Saibene & Margaria (1964) Mechanical work in running - *J Appl Physiol* 19(2) 249-256.
7. Cavagna G.A., Heglund N.C. & Taylor C.R. (1977): Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. - *Am J Physiol* 233: 243-2.
8. McMahon T.A.(1985): The role of compliance in mammalian running gaits. - *J exp Biol* 115: 263-282.
9. Bernstein N.A.(1967): *The coordination and regulation of movements. Pergamon*, London.
10. Blickhan R.(1989): The spring-mass model for running and hopping. - *J Biomech* 22(11/12): 1217-1227.
11. Lee C.R., Farley C. (1998): Determinant of the center of mass in human walking and running. - *J exp Biol* 201(pt 21): 2935-2944.
12. Full R.J., Koditschek D.E.(1999): Templates and anchors: neuromechanical hypotheses of legged locomotion on land. – *J exp Biol* 202(Pt 23), 3325–3332.
13. McMahon T.A. & Cheng G.C. (1990): The mechanics of running: how does stiffness couple with speed? – *J Biomech* 23 (Suppl. 1): 65-78.