Quadrupedal Mammals as Paragons for Walking Machines

H. Witte [1], R. Hackert [1], W. Ilg [2], J. Biltzinger [1], N. Schilling [1], F. Biedermann [3], M. Jergas [4], H. Preuschoft [5] and M. S. Fischer [1]

[1] Institut für Spezielle Zoologie und Evolutionsbiologie, Friedrich-Schiller-Universität Jena, Erbertstraße 1, D-07743 Jena, Germany, witte@pan.zoo.uni-jena.de
[2] Forschungszentrum Informatik, Interaktive Diagnose- und Servicesysteme, TU Karlsruhe, Haid-Und-Neu-Straße 10-14, D-76131 Karlsruhe, Germany, ilg@fzi.de
[3] AG Motorik, Institut für Pathophysiologie, Klinikum der Friedrich-Schiller-Universität Jena, Erfurter Straße 35, D-07740 Jena, Germany, FBIE@moto.uni-jena.de
[4] Radiologische Universitätsklinik St. Josef-Hospital, Ruhr-Universität Bochum, Gudrunstraße 56, D-44791 Bochum, Germany, Michael.D.Jergas@ruhr-uni-bochum.de,
[5] Abteilung für Funktionelle Morphologie, Institut für Anatomie, Ruhr-Universität Bochum, MA 0/44, D-44780 Bochum, Germany, Holger.Preuschoft@ruhr-uni-bochum.de

Abstract

The idea of building artificial animals is an old dream of manhood, handed down through centuries by mythology and poetry. May it be the Troian horse, Olympia the puppet or L. A. Ryggs "Mechanical horse", always the concepts aimed at an artificial humanoid or at reverse engineering of one of man's pets. Not surprisingly Sony's ® "AIBO" as the first commercially available "animate" is a biomomimetic copy of a pet. This anthropocentric approach ignores the fact that ancestral animals as well as most of the currently living animals are and were small – in the size of a mouse or a rat. We and our pets inherited most of our locomotory capabilities from the ancestral mammals, adapting mechanisms and control by only a a small amount in comparison to what happened 200,000,000 years ago when "modern" mammals were derived from reptile-like forms in a dramatical "reconstruction process". "Biological inspiration" of walking machines using mammals as paragons has to be founded on knowledge about the basic principles of mammalian locomotion, visible in small species. From this starting point, special locomotory adaptations of large cursorial mammals like humans, camels or horses may be identified and seperated from what is our common evolutionary heritage.

1. Introduction

Does nature provide better constructive solutions than engineers are able to invent? The current fashion-like approach of "back to nature" in the engineering sciences (which in its core is romantic and thus some 200 y old) yet did not result in obviously improved features of products. The original bionic approach led to pure biomimikry, and with the lack of adapted materials the simple copying of natural constructions in most cases could not result in improved technology. But perhaps should "learning from nature" be understood as the systematic analysis and understanding of biological principles and its transfer into machines by technical means? To test this approach the transfer of a functions tested by evolution for several 100 My promises best results. Legged locomotion in this context is of highest interest for engineers constructing non- wheel-driven vehicles as well as for biologists.

Biological Inspiration of the building of a walking machine may choose its paragons from the whole variety of species described by zoology. Terrestrial legged animal locomotion is a principle which seems to be under high evolutionary pressure what concerns the mechanical needs and solutions, since the overall motion of cockroaches [cf. Garcia et al., this issue] and cursorial mammals like horses may be explained by the same simple equations describing spring-mass systems [1], even if the neural control structures of these only far-related animals are quite different. But on the other hand, the morphological differences between species, base of classical taxonomy, indicate that these functional solutions may be realised by several mechanisms.

Historically the ideas for realising animates mainly aimed at humanoids for service purposes, or at man's pets, if higher loads were planned to be carried. "The Mechanical Horse" [2] (fig. 1) nicely illustrates this anthropocentric approach by simply making copies of pets, which from a biological perspective is a very inefficient way to provide engineers the informations they need for the construction of a technical walking machine.

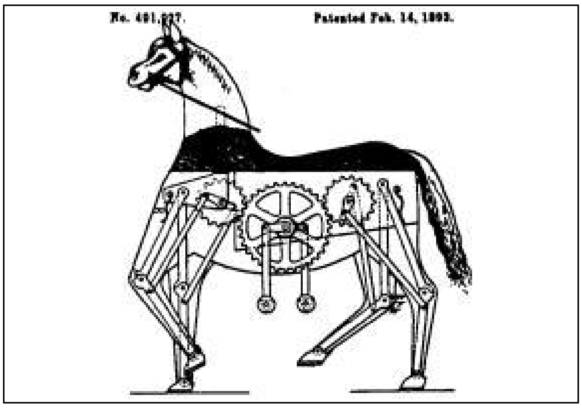

Figure 1: "The Mechanical Horse", patented for L. A. Rygg 1893. [2]

From an evolutionary point of view, man and his pets are cursorial specialists each, showing morphological adaptations to the mechanical needs of species-specific locomotion. This specialisation is derived from a complete chain of heritage without any gap, with only slight modifications from generation to generation. Thus today's structural, mechanical, neural needs in each animal have to interact with evolutionary "decisions" millions of years of age old. Once a switch was turned, and it directed development and the range of possible adaptations in an irreversible manner. All recent animals have to deal with the material properties of musculature, all are controlled by a central nervous system which with the same main locomotory control functions was available already 200 My ago. In reptiles, which seperated from mammals at least at that time, the motoneuron pools for the extremities have the same locations as in mammals [3]. A morphological and functional convergence to the current situation from different starting points has only a low probability.

Biomometic copying of the specialist "horse" into a walking machine without knowing about the functional and evolutionary background which led to this biological solution thus is programmed to fail. But how to uncover the share of evolutionary heritage in relation to that of adaptations to current needs? Surprisingly, most of the living mammals and the ancient representants of the mamalian "stem line" own a common property: they are and were small and light-weighted, with body masses less than 1 kg (fig. 2).

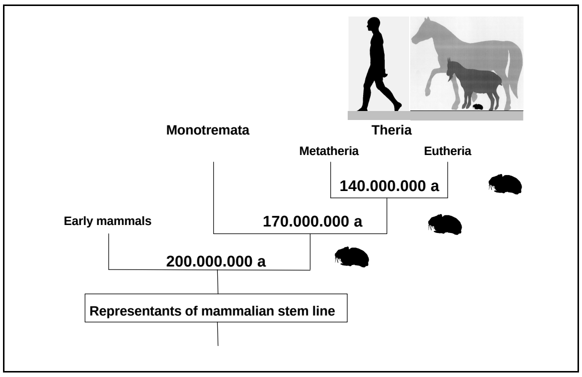

Figure 2: Most of the living mammalian species and the ancestors of modern mammals are and were small. [4]

They all look more or less alike (here demonstrated by the potograph of a pika *Ochotona rufescens*, fig. 3) – some species owning a tail, some not – and, what have shown our own studies of the recent years, move in quite comparable manner, as well as what concerns kinematics as dynamics [5-10]. This is the reason why we suppose that small mammals may teach us the basic principles of mamalian locomotion. On this basis we may derive the special adaptations of large mammals like horses, which are the traditional load carrying "walking machines" of man, to special environmental needs.

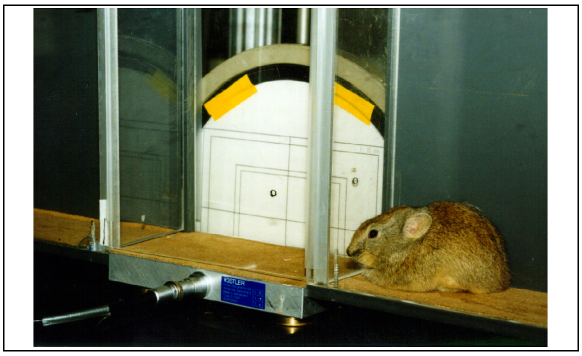

Figure 3: Pika (*Ochotona rufescens*) sitting near the amplifier of a cineradiographic apparatus (Philips®, 150 frames /sec).
In front of the device a Kistler® force plate (200 mm x 120 mm). [4]

To transfer these principles into a machine by technical means, thus extending the catalogue of possible technical solutions, not to substitute techniques by biology is the bionic strategy realised by the programm "Autonomous Walking", granted by the German Research Council DFG.

2. Small mammalian quadrupeds

Cineradiographies taken with the apparatus shown in fig. 3 show that 30 % or more of spatial gain during cyclic locomotion of small mammals is produced by sagittal bending of the trunk for more than 40° (fig. 4). The vertebral column and its driving musculature (paravetrebral and in the thoracic/abdominal wall) are the "main engines" of the animals.

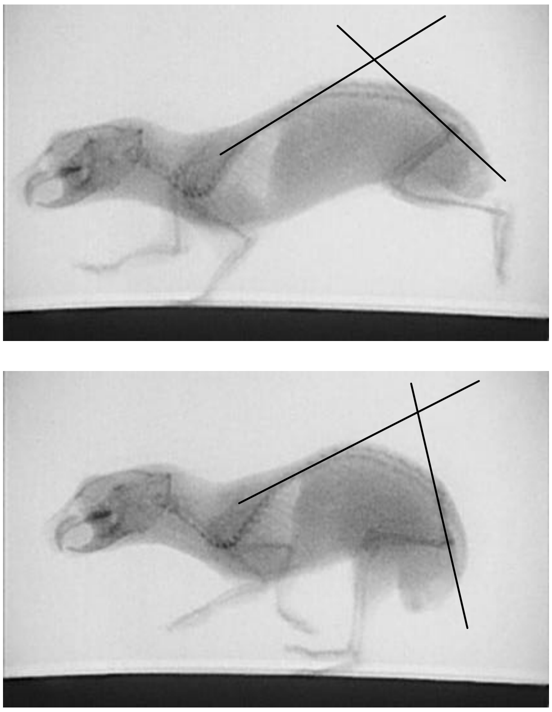

Figure 4: Crouching of the trunk and bending of the vertebral column of a pika (*Ochotona rufescens*) during cyclic locomotion (half-bound). The pelvis is coupled fix to the vertebral column and thus indicates its orientation.

Even between not nearly related species the configurations of the extremities during the locomotion cycle are quite comparable, rather independantly of the gait pattern chosen. This observation allows us to abstract leg movement into the stick figures of an idealized mammal (fig. 5).
A pantograph, which is more or less rectangular, during about 90° of rotation around the legs' bearings at the trunk in the stance phase is crouched to guide the animal's center of mass in a spring-mass system. The springs are muscles, the stiffer and faster ones mainly serving as bi-articular, tunable coupling elements, the compliant slower mono-articular ones mainly offering the possibility to elastically store energy (fig. 6).

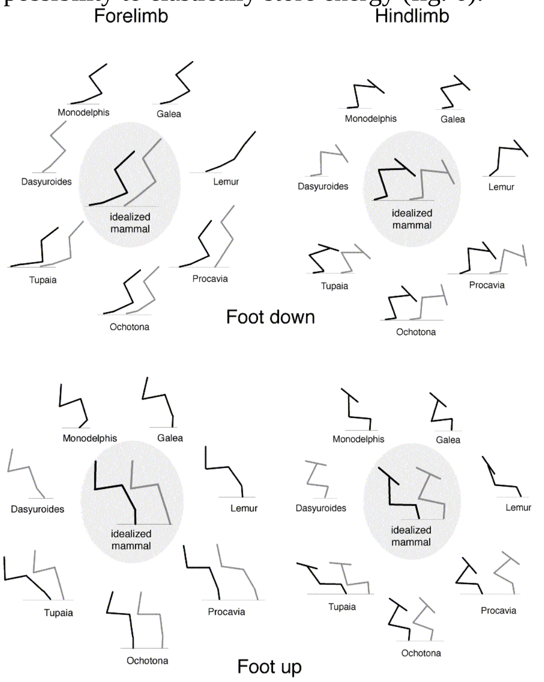

Figure 5: Stick figures of the legs of a variety of small mammals at the reversal points of a motion cycle (foot down, foot up).
The grey shaded ellipses contain the stick figures of an "idealized mammal". [11]

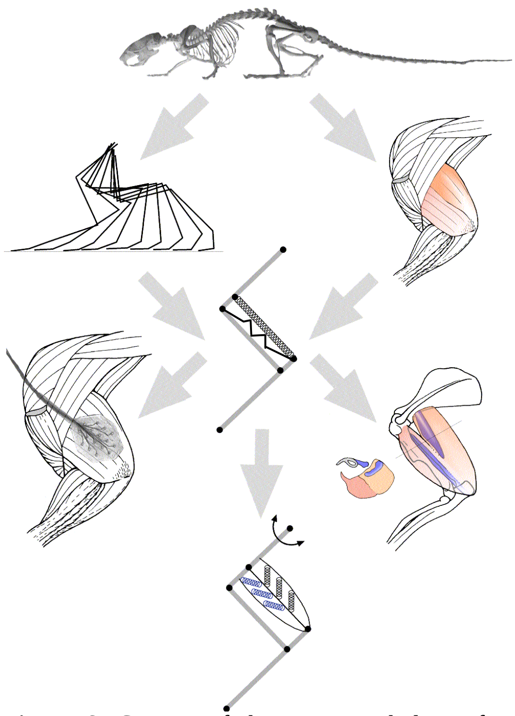

Figure 6: Concept of the "pantograph leg" of small mammals. This model is derived from cineradiography,

topographic typing of muscle fibres and electromyography, in a study on twelve species. [4]
Main elements of the springs are the muscle bellies, containing elastic proteins like titin and nebulin [12, 13]. Combining cineradiographic data with force data yields the results that joint torques in the extremities are rather uniform, independent of the species under study (fig. 7).

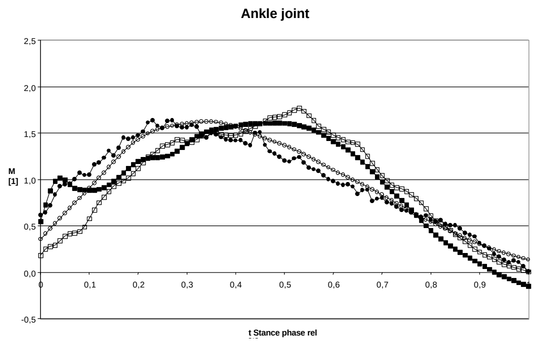

Figure 7: Comparison of the joint torques of four species of small mammals (two species owning a tail and two without a tail).

Interlimb coordination shows no distinct phase shift patterns allowing to identify "gaits", synchronous and symmetrical patterns are chosen in high variability and may be combined with one each other from one step to the next. Speed gain mainly is achieved by an increase of step frequency (decrease of step duration, fig. 8), in extreme keeping half-bound coordination schemes over a tenfold range of velocity.

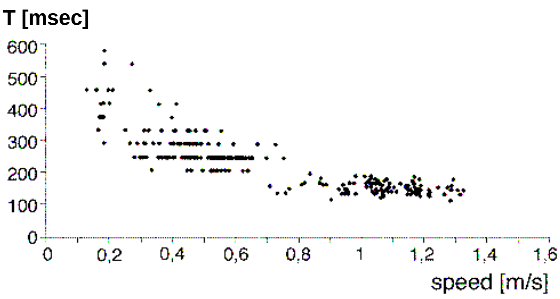

Figure 8: Cycle duration of the half-bound of a pika (*Ochotona rufescens*) as a function of speed. [11]

3. Large mammalian quadrupeds

On the basis of the above described principles of the functional morphology of small versatile mammals we are able to point onto the special adaptations of the evolutionary younger, large mammals, used by man as load-carrying pets.
Large cursorial mammals like horses use motions of their vertebral columns in notable, but much lower extents than small mammals do (fig. 9).

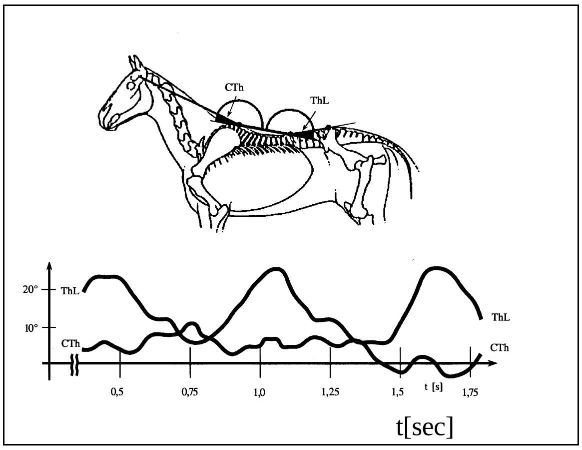

Figure 9: Bending excursion of the vertebral column of a horse during gallop. Data taken from high-speed films (200 frames/sec).

Due to the decreasing muscular capabilities with growing body mass (load is increasing by the third power of length, muscle forces are proportional to the cross sectional areas of muscles, which only increase by the square of length) the leg construction is extended, the long elements are of uneven length, the long tendons of the muscles serve as springs (fig. 10).

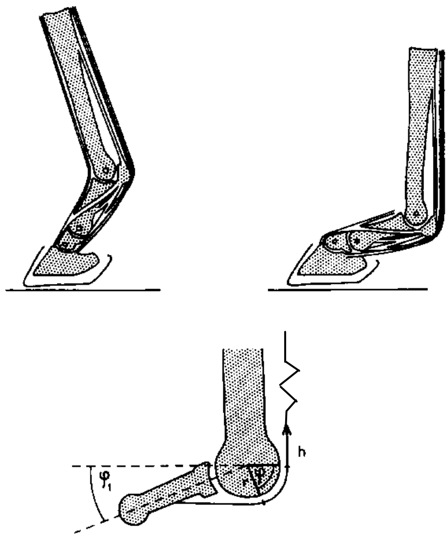

Figure 10: The spring construction formed by the tendon of the long finger flexor of a horse, acting around the fetlock joint. [14]

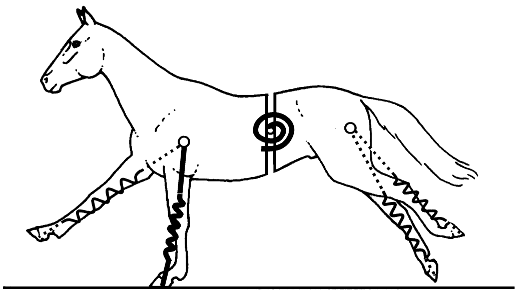

Figure 11: Simple model of a horse in gallop.

These springy legs interact with a bending beam in the trunk [15] (fig. 11). Collagenous tendons own fixed elastic properties, the spring-mass systems have rather fixed resonance frequencies. The consequence is that horses show the well-known phenomenon we call "gaits" (fig. 12).

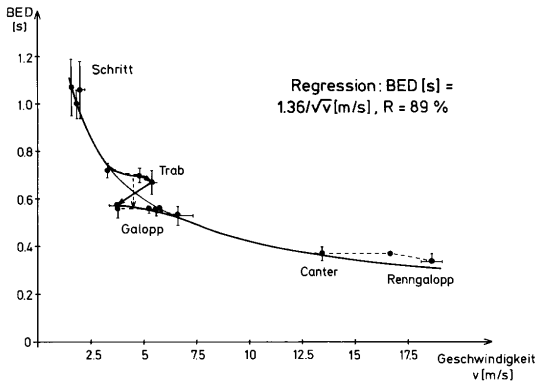

Fig 12: Cycle duration of a horse as a function of speed. Within one gait the frequency is kept rather constant. [16]

4. Principles to be transferred into a machine

The main influence factor on the extension of the legs and the reduction of sagittal spine bending in large mammals seems to be the limited range of adaptibility of structural properties of the materials of the locomotor apparatus (producable tension in muscles, sustainable tension in support tissues, Young's modulus). In our first "naive" approach of transferring principles of natural locomotion into a four-legged technical walking machine ["BISAM II", cf. Ilg et al., this issue] we assume that these limitations may be overcome by technical materials. Thus we construct the machine as an enlarged small mammal, hoping on small mammals' versatility in combination with large mammals' load carrying capacities. If our simulations and results of experiments identify limitations of currently available technical materials for these purposes, we shall follow the adaptive principles shown by large mammals. In detail this leads to the following rules for our basic construction:

1. Use rectangular pantograph legs with minimally three segments (what concerns proportions cf. Blickhan et al. this issue).
2. Guidance of parallized segment in the pantograph should be realized as a stiff coupling, the coupling of neighboured levers should be more compliant.
3. The leg drive should be located near to or on the trunk (proximal).
4. Tuning of the height guidance of the CoM should be realised by distal elements (near to the ground).
5. Fore- and hindlimbs may have the same construction.
6. Legs should use standard dynamics. Reactive control for needs of propulsion should mainly act on the hindlimbs.
7. In a first step, optimise the leg construction in interaction with a stiff trunk.
8. In the next step, allow sagittal bending of the trunk preferably to lateral bending or torsion.
9. The pivots of the legs may be shifted longitudinally (like in the scapula of a horse).
10. Follow Raibert's and Buehler's principles and do use resonance processes for quadrupedal walking machines!

5. Outlook

Biomechanics is not only humano-mechanics. Extension of our field of view to what is outside of our anthropocentric perspective yields high potential to derive principles from nature, which may enlarge and enrich the engineer's toolbox.

Acknowledgements
The studies were granted by the German Research Council DFG (INK-24 A1/B1 and Fi 410-4). Prof. Dr. Dr. H.-R. Duncker, University of Gießen, and Dr. Alain Puget, University of Toulouse made living animals for functional analyses accessible to us. Dr. L. Peichel, Max-Planck-Institut für Hirnforschung, Frankfurt/Main provided a dead animal for morphometrics. Dr. Haarhaus from IWF Göttingen sustained the realisation

of cineradiographies. Prof. Dr. W. Thonfeld and Dipl.-Ing. K. Urban (Fachhochschule Jena) realised the laser-scanning volumetry of animals.

References

[1] TA McMahon & GC Cheng (1990): The mechanics of running: how does stiffness couple with speed? – J Biomech 23 (Suppl. 1): 65 - 78.

[2] SM Song & KJ Waldron (1989): Machines that walk: the adaptive suspension vehicle. The MIT Press, Cambridge (Mass.).

[3] JM Ryan, J Cushman, B Jordan, A Samules, H Frazer & C Baier (1998): Topographic position of forelimb motoneuron pools is conserved in vertebrate evolution. – Brain Behav Evol 51: 90 – 99.

[4] H Witte, J Biltzinger, N Schilling, H Preuschoft & MS Fischer (1999): Was hat der Sportbiomechaniker von den Ergebnissen biomechanischer Analysen an Tieren? Edition Czwalina, Feldhaus Verlag, Hamburg.

[5] MS Fischer (1994): Crouched posture and high fulcrum. A principle in the locomotion of small mammals: the example of the rock hyrax (*Procavia capensis*) (Mammalia: Hyracoidea). – J Human Evol 26: 501 – 524.

[6] MS Fischer (1998): Die Lokomotion von *Procavia capensis* (Mammalia: Hyracoidea). Ein Beitrag zur Evolution des Bewegungssystems der Säugetiere. - Abh. Naturwiss. Verh. naturwiss. Vereins Hamburg (NF): 33: 1-188

[7] MS Fischer (1999): Kinematics, EMG, and inverse dynamics of the Therian forelimb – a synthetic approach. – Zool Anz 238: 41 – 54.

[8] MS Fischer & R Lehmann (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.

[9] N Schilling & MS Fischer (1999): Kinematic analysis of treadmill locomotion of tree shrews, *Tupaia glis* (Scandentia: Tupaiidae). – Z Saeugetierk 64: 129 – 153.

[10] M Schmidt & MS Fischer (2000): Cineradiographic study of forelimb movements during quadrupedal walking in the Brown Lemur (*Euleumur fulvus*, Primates: Lemuridae). – Amer. J. Phys. Anthropol. 111: 245 - 262.

[11] 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.

[12] K Wang, R McCarter, J Wright, J Beverly & R Ramirez-Mitchell (1991): Regulation of skeletal muscle stiffness and elasticity by titin isoforms. – Proc Natl Acad Sci USA 88: 7101 – 7109.

[13] S Labeit & B Kolmerer (1995): Titins: giant proteins in charge of muscle ultrastructure and elasticity. – Science 270: 293 – 296.

[14] H Preuschoft, C Lesch, H Witte & C Loitsch (1995): Die biomechanischen Grundprinzipien der Gangarten, Insbesondere des Galopps. – In: PF Knesevic, Orthopädie bei Huf- und Klauentieren. Schattauer, Stuttgart: 355 – 370.

[15] RM Alexander, NJ Dimery & RF Ker (1985): Elastic structures in the back and their role in galloping in some mammals. – J Zool (Lond) A207: 467 – 482.

[16] H Witte, C Lesch, H Preuschoft & C Loitsch (1995): Die Gangarten der Pferde: sind Schwingungsmecha-nismen entscheidend? Federschwingungen bestimmen den Trab und den Galopp.– Pferdeheilkunde 11(4): 265 – 272.