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Biomechatronics: How much biology does the engineer need?

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Introduction

The historically well-founded strategy of biological inspiration of the process of technical development ("bionics", JE Steel 1960) is more than ever a concept well acceptable for most engineers. Everyone plans to do so, but only a few at last really do.

Analysing our own experiences with bionic projects, we tried to identify why "all-days-life engineering" does not make use of bionics. In our presentation, we use the report on the process of bionic inspiration of mammalian-like walking machines (bipedal and quadruped) mainly as a vehicle to identify items necessary to make biologists and engineers not only work together but to really interchange. The usual idea that biologists only need to be offered areas of technical application of the biological principles they identify – "Technical Biology" – in our opinion is too short ranging. Analysing the sciences established in the range between biology and engineering (cf. fig. 1), the current problems of missing economic success of bionics, the decreasing interest in functional morphology, and the story of success of sports biomechanics and biomedical engineering seems to teach the following:

One conditio sine qua non for success indeed is the access to a field of application. But more important is a condition, which in its core is based in psychology: the one to apply the biological principles in techniques is the one to pose the scientific question. Otherwise biology offers solutions no engineer has current interest in. The consequence we drew is that we have to teach engineers how to pose questions to biologists (and physician as "applied biologists") in a correct terminology and in a style indicating basic knowledge about and interest in biology. We offer to our students of mechatronics a specialisation in "biomechatronics". In extension of the use of this term at M.I.T. and the University of Twente we not only aim at the application of mechatronics in biomedical engineering, but extend the definition to: "Biomechatronics is using biomedical knowledge for the development and optimisation of mechatronic systems." This covers bionics (biology for engineering) as well as biomedical engineering and its relatives (engineering for biology). The reason for the extension of the area of interest is our convincement that inspiration and application should be linked together in education as well as in science.

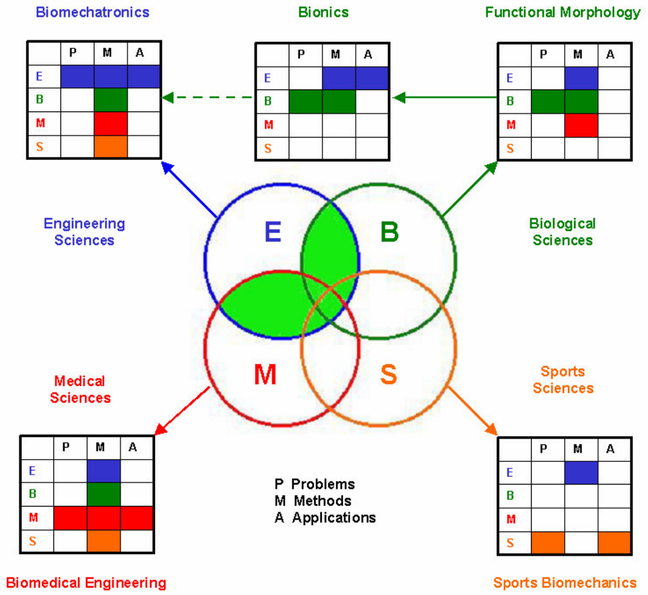

Fig. 1: Biomechatronics

Analyses: Biologically inspired robotics

Pedality

Despite of organisms in the micro-world with their appendices, flagellae and (kino-)cilia, animals using pedal locomotion own an even number of legs and are bilaterally symmetrical: "Bilateria". But things like side preferences during evolution seem to occur by random: the decision on which side of the vertebrate body organs are located is determined by the orientation of the flow of some body fluids during ontogenesis, which depends from one single gene locus influencing the stroke of kinocilia by the conformation of one proteine (the basic concept was proposed as early as in 1959 by Hummel & Chapman and now is confirmed by a series of molecular biological studies). Thus, the decision for an even number of legs may go back to one single mutation which delivered one functional solution – and in evolution never occurred the need or the opportunity to "invent" vertebrate systems with odd number of legs. Consecutively the impression of engineers that the mostly elegant solution of symmetry has mechanical advantages and thus provoked its application in nature may be wrong in its core.

Pragmatism of bionics is the only logical reason to build walking machines with even number of legs – there do exist recent paragons accessible for analyses. Carsten Berns' catalogue of walking machines (Berns 1999) offers a nice overview on walking machines yet realized. Most of them are polypedal (owning three or more pairs of legs), natural paragons like the "centipedal" Dekapodes and the "millipedal" Myriapodes have up to 140 pairs of legs. A lot of machines has three pairs of legs (= six legs). The reasons for this are simple (Cruse et al. 1998):

- Mechanically: six legs allow steady support on at minimum three legs, static stabilization is feasible
- Bionic-historically: when engineers showed interest in animal locomotion, data on stick insects where best accessible:
  - Motion analyses on stick insects are simple, the exosceleton well is representable by rigid body mechanics, joints and their motions are identifiable with minor errors
  - The nervous system owns only few neurons, which are accessible from the outside without greater disturbances of the locomotion of the animal
  - And last but not least experiments on invertebrates (in Germany, where such things where done) do not underly such legal restrictions like experiments on vertebrates

But polypedals in relation to oligopedals need more material, energy and control effort for their own locomotion in relation to oligopedals (one or two pairs of legs) (Witte et al. 2002) – relative payload is lower in polypedals. And in future walking machines have to be looked at as any other vehicle – their main purpose is to carry any load, not their own body.

Aiming at autonomy in energetics and control, oligopedals thus are interesting paragons for walking machines.

But why realisation does last for so long time? In the speed ranges used by animals as well as by machines gravity effects usually are of higher meaning than inertia – reaching stability steadily is a fight against simply breaking down. As oligopedals during locomotion may have periods of two- or single-leg contact, dynamic stabilization is necessary. To realize control hardware and software fast enough for this tasks, current computers still are too slow. But bionics the last years tought us, that due to intelligent mechanics perhaps the best control is the one which is superfluous. Thus the hope to realize oligopedal machines which are vertebro-functional and not only vertebro-morphic has become realistic.

Choice of paragons

Bionic inspiration of bipedal robots mainly follows psycho-social aspects. Even if at present in France by the project ROBOCOQ some work is done transferring principles of the locomotion of birds into robotics, main activities concentrate onto anthropomorphic machines, culminating in systems like those of Honda® or Fujitsu®. The rational behind these developments is pointing to the age structure of societies, with a growing number of elderly people needing physical support and a decreasing number of younger ones being able to provide it. As has been discussed elsewhere in detail (Witte 2002), the consequence for the development of anthropomorphic machines for tasks in households and clinics has to be their metamorphosis to anthropofunctionality – they not only have to look like men, their have to move like them.

The criteria for the choice of paragons for quadrupedal machines have been discussed in our contribution to AMAM '2000 (Witte et al. 2000). Aiming at a machine with generalist skills, the functional morphology of small mammals is the first choice of bionic inspiration.

Controlling kinematics or dynamics?

From a basic technical point of view, walking is comparable to driving. An object represented by its mass distribution has to be moved in all 6 mechaniacl degrees of freedom – the task is a kinematic one. Consecutively, in robotics often kinematic trajectories are subject to control, deriving dynamics necessary to realize them. Observation of animals leads to a quite different impression: Dynamics are provided in a machine-like manner (cf. Witte et al. 2002) by an evolutionary conservative central nervous system performing standard batch jobs (cf. Cheng et al. 1998, Ryan et al. 1998, Grillner 1981 and consecutives, Mussa-Ivaldi & Bizzi 2000), kinematic adaptation is realized by a gear with tunable properties (Mussa-Ivald et al. 1988) including muscle-tendon-springs with adaptive elastic mechanisms (cf. Witte et al. 1995a, b) (Fig. 1).

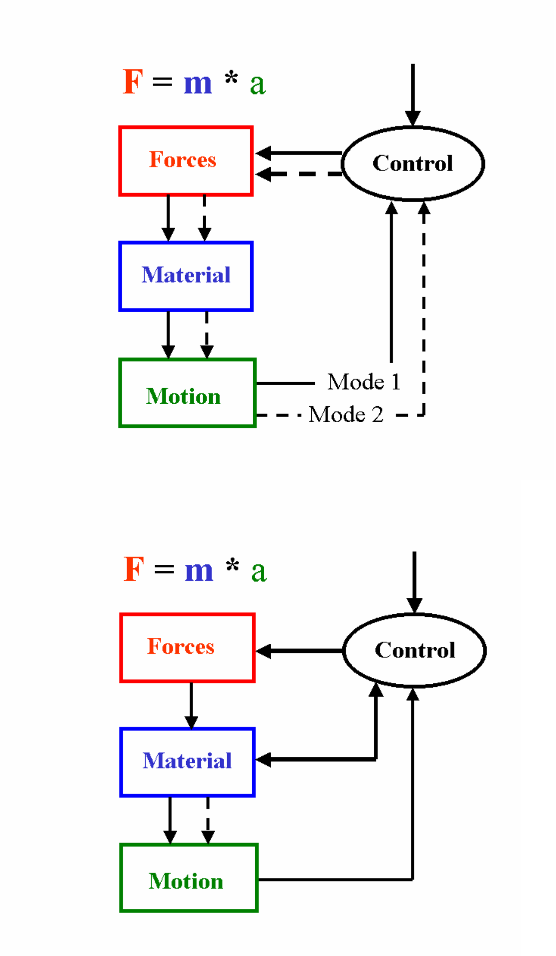

Fig. 2 Control concepts
Top ”Classical”: Forces and torques are induced by the control and transferred into kinematics by a transmission with fixed properties. Sensing kinematics closes feedback loop
Bottom ”Bionic”: Forces and torques are induced by the control and transferred into kinematics by an adaptive transmission, which underlies short-time feedback control. Sensing kinematics mainly serves long-time tuning of control

The knowledge about muscles at present rapidly increases, since biochemistry and molecular biology decovered the existance of elastic “giant proteins”, which in the past simply have been overlooked due to their large size (Wang 1983, 1984; Wang et al. 1991, 1993; Labeit & Kolmerer 1995a, b). These proteins make muscles to actuators with locally high resolved mechanical adaptivity due to post-translational splicing (cf. the overviews in Linke et al. 1996 and Granzier & Labeit 2002).

Hypothesis: vertebrates at the root of oligopedal evolution made use of resonance mechanisms with – due to their small size - high cycle frequencies. Central nervous “computers” were to slow to do the control job just-in-time. Thus adaptive, intelligent mechanics using elasticity (cf. the work of McNeill Alexander, Blickhan, Cavagna, Heglund, Margaria, McMahon, Taylor) with preflexes (cf. Brown & Loeb 1997) and self-stabilization (cf. Wagner & Blickhan 1999, Hackert et al. 2000, Seyfarth et al. 2001) took over. Once a functioning system was realized, in evolution towards larger animals no need occurred to “invent” a control system following the rules of engineering sciences. Even if the engineer’s solution would be better, one has to realize on basic thing: evolution provides solutions which function, not optimal solution (the statement in this clarity and sharpness relies to the evolutionary biologist Martin S. Fischer from Jena).

Mass distribution in natural systems is realized and in technical systems should be realized follwing the principles of functional morphology (D’Arcy Thompson 1917). Biology as “natural history” teaches us that locomotion was developped for trunks – extremities are appendices what concerns the history of development and their function for locomotion. Thus in future compliant trunks offer high poetential for the bionic inspiration of walking machines.

Meta-Analysis: how much biology does the engineer need?

The examples discussed before should have illustrated the high potential of bionic inspiration in engineering sciences. Engineers mostly agree to the sensefulness of “learning from nature” – but in all-days-practice it is not applied. As ha been stated in the introduction, the reason for us seems not to be mainly a rational one but is based on psychology. Construction is a highly creative process based on a lot of hard work. The motivation to take over this work is the opportunity to see own ideas to become substantial – OWN ideas. Engineers hate to be used to realize the ideas of other ones, which perhaps in addition earn most of the money the product carries “only” by having the idea. In addition, the pioneers of bionics offered complete solutions like “lotus-effect-surfaces” of “shark-skinned covers”, that they left no space for creativeness of engineers.

Our conclusion is, that to motivate engineers to apply bionics in practice we have to show them how to pose questions to biology and how to control the process of analyses and syntheses from the beginning. Basic for this purpose is to understand terminology and – by this way – thinking in and rationals of biology. The example on walking machines shown before indicates the need for basic understanding and basic knowledge in the following fields of biological sciences (Botany, Zoology):

- (Comparative) (functional) anatomy
- Developmental biology
- Taxonomy
- Physiology
- Biochemistry
- Genetics and molecular biology
- Ecology
- Strategies and methods of bionic inspiration

As has been stated in the introduction, we realize this concept exemplarily in conjunction with an education in "Mechtronics in biomedical engineering" (fig. 3). First students with Master degree in 2004 will test the solidity of the concept in industrial employment.

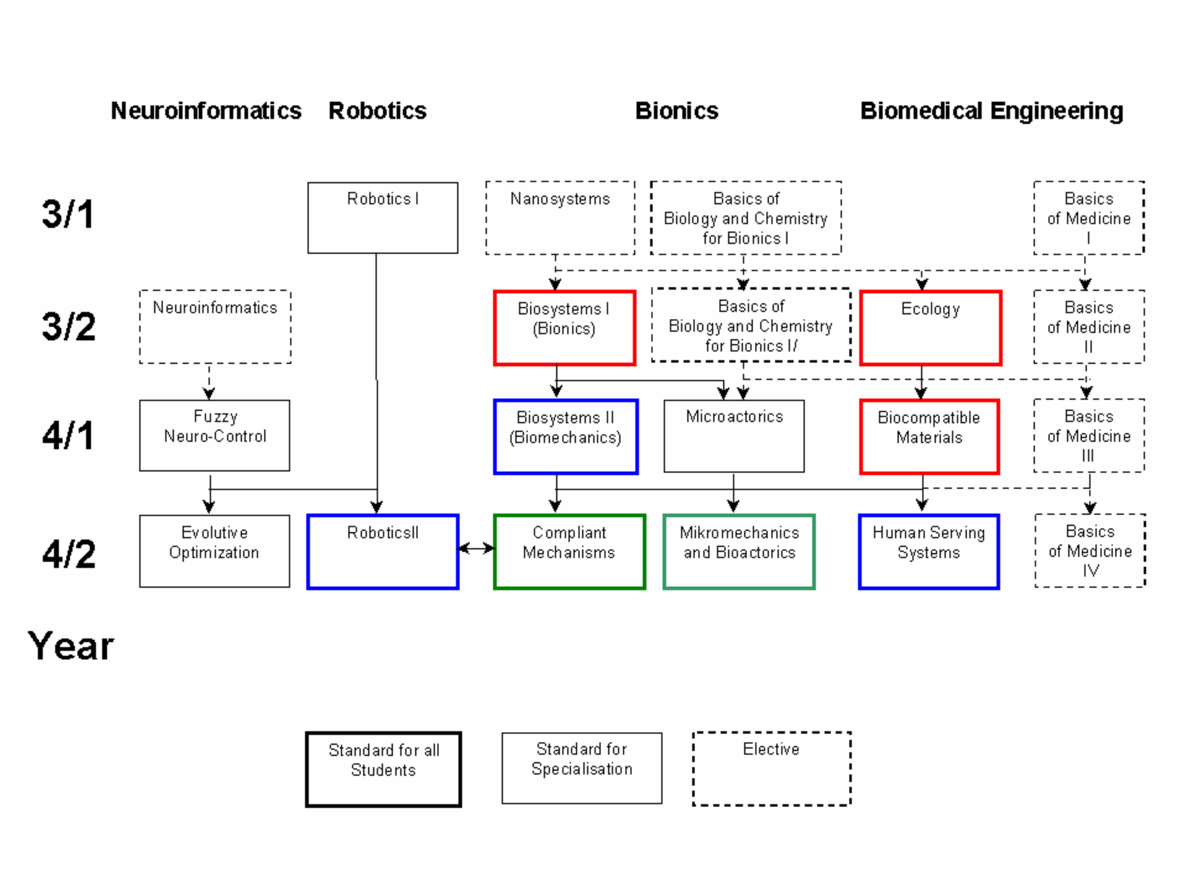

Fig 3.: Master studies of Biomechatronics at Technische Universität Ilmenau

References

1. Adams, D. (1987): The hitchhiker's guide to the galaxy. - Ballantine Books, New York.
2. Alexander, R. M. & Bennet-Clark, H. C. (1977): Storage of elastic strain energy in muscle and other tissues. - Nature **265**: 114 -117.
3. Alexander, R. M. & Dimery, N. J. (1985): Elastic properties of the fore foot of the donkey (*Equus asinus*). - J. Zool. Lond. **A205**: 511-524.
4. Alexander, R. M. & Jayes, A. S. (1983): A dynamic similiarity hypothesis for the gaits of quadrupedal mammals. - J. Zool. **201**: 135-152.
5. Alexander, R. M. (1988a): Elastic mechanisms in animal movement. - Cambridge University Press.
6. Alexander, R. M. (1988b): Why mammals gallop. - Amer. Zool. **28**: 237-245.
7. Alexander, R. M. (1989): On the synchronization of breathing with running in wallabies (*Makropus spp*.) and horses (*Equus caballus*). - J. Zool. Lond. **218**: 69-85.
8. Alexander, R. M. (1990): Elastic mechanisms in the locomotion of vertebrates. - Neth. J. Zool. **40** **(1-2)**: 93-105.

9. Alexander, R. M., Dimery, N. J. & Ker, R. F. (1985): Elastic structures in the back and their role in galloping in some mammals. - J. Zool. Lond. **A207**: 467-482.
10. Alexander, R. M., Maloiy, G. M. O., Ker, R. F., Jayes, A. S. & Warui, C. N. (1982): The role of tendon elasticity in the locomotion of the camel (*Camelus dromedarius*). - J. Zool. **198**: 293-313.
11. Blickhan, R. (1989): The spring-mass model for running and hopping. - J. Biomech. **22**: 1217-1227.
12. Cavagna, G. A., Heglund, N. C. & Taylor, C. R. (1977a): Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure. - Am. J. Physiol. **233**: 243 - 261.
13. Berns, C. (1999): Laufmaschinenkatalog. http://www.fzi.de/ipt/WMC/walking_machines_katalog/walking_machines_katalog.html
14. Brown, I. E. & Loeb, G. E (1997): A reductionist approach to ccreating and using neuromusculosceletal models. - In: Winters J. M. & Crago, P. E. (Hrsg.) Biomechanics and neural control of posture and movement.
15. Cheng, J., Stein, R.B., Jovanovic, K., Yoshida, K., Bennett, D.J. & Han, Y. (1998): Identification, localization, and modulation of neural networks for walking in the mudpuppy (Necturus maculatus) spinal cord. - Journal of Neurosciences **18 (11)**: 4295-4304.
16. Cruse, H., Dean, J. & Ritter, H. (1998): Die Entdeckung der Intelligenz oder Können Ameisen denken? Intelligenz bei Tieren und Maschinen. - Verlag C. H. Beck, München.
17. D'Arcy Thompson (1917): On growth and form. Reprint Cambridge University Press, Cambridge.
18. Dimery, N. J., Alexander, R. M. & Deyst, K. A. (1985): Mechanisms of the ligamentum nuchae of some artiodactyls. - J. Zool. Lond. **A206**: 341-351.
19. Dimery, N. J., Alexander, R. M. & Ker, R. F. (1986): Elastic extension of leg tendons in the locomotion of horses (*Equus caballus*). - J. Zool. Lond. **A210**: 415-425.
20. Granzier, H. & Labeit, S. (2002): Topical review: Cardia titin: an adjustable multi-functional spring. - J. Physiol. **541(2)**: 335-342.
21. Grillner S (1981): Control of locomotion in bipeds, tetrapods, and fish. – In: (V. B. Brooks, ed) Handbook of Physiology. Section 1. The nervous system, Vol II, Part 2, Amer. Physiol. Soc., Bethesda. 1179-1236.
22. Grillner, S, Buchanan, J.T., Wallen, P. & Brodin, L. (1988): Neural control of locomotion in lower vertebrates: From behavior to ionic mechanisms. - In: (Cohen AH, Rossignol S., Grillner, S. eds.) Neural control of rhythmic movements in vertebrates. Whiley & Sons, New York, Chichester, Brisbane. 1-40.
23. Grillner, S. & Wallen. P (1999): On the cellular bases of vertebrate locomotion. - In: M.D. Binder (ed) Progress in Brain Research Vol 123. Peripheral and spinal mechanisms in neural control of movement. Elsevier, Amsterdam. Lausanne, New York, Oxford, 297-309.
24. Grillner, S. & Zangger, P. (1975): How detailed is the central pattern generation for locomotion? - Brain Res. **88(2)**: 367-371.
25. Grillner, S., Cangiano, L., Hu, G., Thompson, R., Hill, R., & Wallen, P. (2000): The intrinsic function of a motor system--from ion channels to networks and behavior. - Brain Res. 886 (1-2): 224-236.
26. Heglund, N. C. & Taylor, C. R. (1988): Speed, stride frequency and energetic cost per stride: how do they change with body size and gait? – J. exp. Biol. **138**: 301 – 318.
27. Hildebrand, M. (1985): Walking and running. - In: Hildebrand, M.,, Bramble, D. M., Liem, K. F. & Wake, D. B.(eds.), Functional vertebrate morphology. The Harvard University Press, Cambridge, 38-57.
28. Hummel K. P. & Chapman D.B. (1959): Visceral inversion and associated anomalies in the mouse. - J. Hered. **50**:9-13.
29. Ilg. W., Berns, K., Dillmann, R., Fischer, M. S., Witte, H., Biltzinger, J., Lehmann, R. & Schilling, N. (1998): From quadrupedal animals to quadrupod animates. Biologically inspired construction and control architecture for a quadruped walking machine. - Proc. ISAB 5th International Conference on Simulation of Adaptive Behavior. The MIT Press Cambridge, Massachusetts and London, England, 400-408.
30. Labeit, S. & Kolmerer, B. (1995a): Titins: giant proteins in charge of muscle ultrastructure and elasticity. - Science **270**: 293 _ 296.
31. Labeit, S. & Kolmerer, B. (1995b): The complete primary structure of human nebulin and its correlation to muscle structure. - J. Mol. Biol. **248**: 308-315.
32. Linke, W.A., Ivemeyer, M., Olivieri, N., Kolmerer, B., Ruegg, J.C. & Labeit, S. (1996): Towards a molecular understanding of the elasticity of titin. - J. Mol. Biol. **261**: 62-71.
33. McMahon, T. A. & Cheng, G. C. (1990): The mechanics of running: how does stiffness couple with speed? - J. Biomech. **23(1)**: 65 - 78.
34. McMahon, T. A. (1973): Size and shape in biology. - Science **179**: 1201-1204.
35. McMahon, T. A. (1975): Using body size to understand the structural design of animals: quadrupedal locomotion. - J. Appl. Physiol. **39**: 619-627.
36. McMahon, T. A. (1977): Scaling quadrupedal galloping: frequencies, stresses, and joint angles. - In: Pedley, T. J. (eds.), Scale effects in locomotion. Academic Press, London, 143-151.
37. Mussa-Ivaldi, F. A. & Bizzi, E. (2000): Motor learning through the combination of primitives. - Philos. Trans.R. Soc. Lond B Biol. Sci. **355**(1404): 1755-1769.
38. Mussa Ivaldi, F. A., Morasso, P. & Zaccaria, R. (1988): A distributed model for representing and regularizing motor redundancy. - Biol. Cybern. **60**: 1-16.
39. Ryan, J.M., Cushman, J., Jordan, B., Samules, A., Frazer, H. & Baier, C. (1998): Topographic position of forelimb motoneuron pools is conserved in vertebrate evolution. - Brain Behaviour and Evolution **51**: 90-99.
40. Seyfarth, A., Günther, M. & Blickhan, R. (2001): Stable operation of an elastic three-segment leg. - Biological Cybernetics **84 (5)**: 365-382.
41. Wagner, H & Blickhan, R. (1999): Stabilizing function of skeletal Muscles: an analytical investigation. – J. Theor. Biol. **199**: 163-179.
42. Wang, K. & Ramirez-Mitchell, R. (1983): A network of transverse and longitudinal

intermediate filaments is associated with sarcomeres of adult vertebrate skeletal muscle. - J. Cell Biol. **96**: 562 - 570.

43. Wang, K. (1982): Purification of titin and nebulin. - Methods Enzymol. **85** Pt B:264-274.
44. Wang, K. (1984): Cytoskeletal matrix in striated muscle: the role of titin, nebulin and intermediate filaments. - Adv. Exp. Med. Biol. **170**: 285 - 305.
45. Wang, K., McCarter, R., Wright, J., Beverly, J. & Ramirez Mitchell, R. (1991): Regulation of skeletal muscle stiffness and elasticity by titin isoforms. - Proc. Natl. Acad. Sci. USA **88**: 7101-7109.
46. Wang, K., McCarter, R., Wright, J., Beverly, J. & Ramirez Mitchell, R. (1993): Viscoelasticity of the sarcomere matrix of skeletal muscles. The titin-myosin composite filament is a dual-stage molecular spring. - Biophys. J. **64(4)**: 1161-1177.
47. Witte, H. (2002): Hints for the construction of anthropomorphic robots based on the functional morphology of human walking. - Journal of the Robotic Society of Japan **20(3)**: 247-254.
48. Weber W. E. & Weber E. F. W. (1836): Ueber die Mechanik der menschlichen Gehwerkzeuge. Dietrich, Göttingen.
49. Witte, H. (1992): Über mechanische Einflüsse auf die Gestalt des menschlichen Körpers. – M.D. thesis, Bochum.
50. Witte, H., Ilg, W., Eckert, M., Hackert, R., Schilling, N., Wittenburg, J., Dillmann, R. & Fischer, M. S. (2000): Konstruktion vierbeiniger Laufmaschinen. – VDI-Konstruktion **9-2000**: 46-50.
51. Witte, H., Biltzinger, J., Hackert, R., Schilling, N., Schmidt, M., Reich, C. & Fischer, M. S. (2002): Torque patterns of the limbs of small therian mammals during locomotion on flat ground. - J. Exp. Biol. **205(9)**: 1339-1353.
52. Witte, H., Lesch, C., Preuschoft, H. & Loitsch, C. (1995a): Die Gangarten der Pferde: sind Schwingungsmechanismen entscheidend? Teil I: Pendelschwingungen der Beine bestimmen den Schritt. - Pferdeheilkunde **11(3)**: 199-206.
53. Witte, H., Lesch, C., Preuschoft, H. & Loitsch, C. (1995b): Die Gangarten der Pferde: sind Schwingungsmechanismen entscheidend? Teil II: Federschwingungen bestimmen den Trab und den Galopp. - Pferdeheilkunde **11(4)**: 265-272.
54. Witte, H., Recknagel, S., Lesch, C., Rao, J. G. & Preuschoft, H. (1997): Is elastic energy storage of quantitative relevance for the functional morphology of the human locomotor apparatus?