FUNCTIONAL MORPHOLOGICAL AND PHYSIOLOGICAL ASPECTS OF HUMAN LOCOMOTION AND POSTURE

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Contents

Summary

We would like to emphasize the following points:

- The use of the spine and trunk in human locomotion is as important in humans as it is in the locomotion of other tetrapodes: the ancestors and relatives of the species *Homo sapiens*. The spine and trunk, and their musculature drive locomotion; extremities transfer and modulate it.
- The occurrence of a waist, especially in humans, indicates the importance of rotations between the upper trunk (head, neck, and thorax) and the lower trunk (pelvis) with an elastic joint (spine, paravertebral, and abdominal musculature) within the rump. Of most importance seems to be the torsional twist around longitudinal axes.
- Human walking is an interplay between masses, gravity, and elasticity that is modulated by musculature. Rigid body mechanics alone are insufficient to describe human walking.
- Posture control is a dynamic process that is necessary for efficient human locomotion, and also for other basic motor functions, such as standing and sitting. The systems underlying these motor functions interact.

- During the locomotion of vertebrates—including humans—a task-specific activation of the motor system is revealed, which is modulated by individual motor realization strategies.

1. Introduction: the Common Mammalian Heritage

Humans are placental mammals, tetrapodes, vertebrates—those zoological classifications in medical science that only seem to be of interest in the context of drug tests using animals as measuring devices. However, as we make use of the common genetic heritage of humans and the mouse in pharmaceutics, we have to be aware that the common descent of mammals also restricts our therapeutical approaches. Human beings are no new invention—our species incorporates the developmental possibilities and restrictions of our ancestors. Evolutionary selection in former times may have acted on our precursors under quite different ecological circumstances. Evolution has not flowed purposefully towards humans as the “Lords of Creation.” The outcome is the result of a zigzag course through adaptations towards circumstances that have changed during time. No species is “optimal.” All are adapted to fulfill the needs of survival, and as long as they perform this function there exists no driving force towards an optimum. In addition, knowledge about the phylogenetic development of humans is as important for physicians as knowledge about their ontogeny, so that they can avoid therapeutic approaches that aim to act against developmental constraints incorporated in our genetic heritage—a fight that cannot be won.

The bipedal specialization of humans, with its unique functio-morphological adaptations, especially provokes anthropocentric approaches in the therapy of diseases of the human locomotor apparatus. For the locomotion humans use have the same principles as most other mammals. In the following, we shall explain some of the key features of mammalian locomotion and their implications for human medicine.

- The main locomotory organ of vertebrates is the trunk, which incorporates the structure defining the whole group: the vertebral column. Small, ancestral mammals realize up to 50% of the spatial gain per movement cycle of the whole body (contributed by the overlapping step lengths of the extremities and by flight phases) by motions of the trunk. Humans have reduced sagittal bending of the trunk and spine, but the systematic use of deformations of the trunk during walking still indicates the function of a nonrigid trunk for locomotion; be it as a pacemaker for the extremities giving a central clocking mode, as an energy source (which is the subject of controversial debate), or to provide optimized conditions for the use of self-stabilizing mechanisms.
- The stem line of mammals is characterized by sagittalized extremities with three long segments: scapula, humerus, and lower arm, and the corresponding leg segments of the thigh, shank, and elongated metatarsus. The human hindlimb still owns the ancestral three-segmented construction, showing proportions adapted to the needs of self-stabilization. The human forelimb seems to be reduced to two long segments—the locomotor meaning of the scapula is usually ignored due to the fact that in humans this bone is in an rectangular orientation to the plane of motion. As a consequence of the missing kinematic coupling between forelimbs and ground in bipedalism, misfunctions of the scapular pivot only lead to dynamic disturbances,

which may generally be compensated for by additional input of energy into the system with consecutive disturbances of other parts of the locomotor system.

- Neural control of locomotion, for both the trunk and the extremities, is derived from excitatory waves running down the spinal cord cranio-caudally. Spatiotemporal redistribution of these excitations from the spinal cord onto the musculature is realized by nerve plexus; different locomotor schemes of the extremities may correlate with different formations of plexus.
- In locomotion, energy is periodically transferred between its different subentities of kinematic and potential energy. Potential energy may be stored in the gravitational field, which leads to the concept of the extremities forming pendula, or it may be stored in elastic springs. In large master-cursors, such as horse and camel, these springs may be realized by collagen in tendons or by elastic giant proteins such as titin or nebuline in the muscle bellies of all mammals, including humans.

For limbed animals, the mechanics of terrestrial locomotion follow surprisingly simple common rules. Boundary conditions are given by morphology (body mass and body height: the results of evolution), gravitation (a natural constant), and elasticity (material properties, which seem to have been remarkably unchanged during mammalian evolution). Timing is restricted by neural mechanisms, which may be derived from reptile precursors more than 140 million years ago. Since, within one species, such as *Homo sapiens*, proportions and mass distribution are fairly common for all individuals (these features formed the basis for the differentiation of species in zoological terms), locomotor capabilities are quite restricted within the limitations of our evolutionary heritage. Knowledge about these facilitates rational therapy.

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Bibliography

Biedermann F., Schumann N.P., Fischer M.S., and Scholle H.C. (2000). Surface EMG-recordings using a miniaturized matrix electrode: a new technique for small animals. *Journal of Neuroscience. Methods* 97(1), 69–75.

Büschges A. and El Manira A. (1998). Sensory pathways and their modulation in the control of locomotion. *Current Opinion in Neurobiology* 8, 733–739. [Reviews studies about the impact of sensory information on control of locomotion.]

English A.W. and Letbetter W.D. (1982). Anatomy and innervation patterns of the cat lateral gastrocnemius and plantaris muscles. *American Journal of Anatomy* 164, 67–77. [Presents results on muscular compartments that are innervated by the primary branches of the nerve to the muscle.]

Fischer M.S. (1999). Kinematics, EMG, and inverse dynamics of the therian forelimb – a synthetic approach. *Zoologischer Anzeiger* 238, 41–54. [Provides an overview on mammalian limb function.]

Grillner S. Cangiano L., Hu G., Thompson R., Hill R. and Wallen P. (2000). The intrinsic function of a motor system – from ion channels to networks and behavior. *Brain Research* 886(1-2), 224–236. [Review of the neuronal organization of pattern generators and locomotor networks based on in vitro preparations of the spinal cord of the lamprey. The concept of pattern generators driving rhythmic locomotion is introduced and intensively studied by Sten Grillner and his group.]

Mussa-Ivaldi F.A. and Bizzi E. (2000). Motor learning through the combination of primitives. *Philosophical transactions of the Royal Society of London*. *Series B: Biological Sciences* 355(1404), 1755–1769. [Introduces the concept of movement modules.]

Preuschoft H., Witte H., and Demes B. (1992). Biomechanical factors that influence overall body shape of large apes and humans. *Topics in Primatology*, Vol. 3 (ed. S. Matano, R.H. Tuttle, H. Ishida, and M. Goodman), pp. 259–289. Tokyo: University of Tokyo Press.

Scholle H.Ch., Schumann N.P., Biedermann F., Stegeman D.F., Graßme R., Roeleveld K., Schilling N., and Fischer M.S. (2001). Spatiotemporal surface EMG characteristics from rat triceps brachii muscle during treadmill locomotion indicate selective recruitment of functionally distinct muscle regions. *Experimental Brain Research* 138, 26–36. [Investigates the selective muscle activation of rat triceps brachii during locomotion considering the three-dimensional muscle fiber distribution.]

Schumann N.P., Grosch J., Bradl I., Anders Ch., and Scholle H.Ch. (1996). Lumbales Oberflächen-EMG beim Sitzen. *Prävention von berufs- und arbeitsbedingten Erkrankungen*, Vol. 2 (ed. S. Radandt, R. Grieshaber, and W. Schneider), pp. 255–269. Leipzig, Germany: Erfurter Tage. monade Verlag und Agentur, Rainer Rodewald.

Selverston A. (1999). General principle of rhythmic motor pattern generation from invertebrate CPGs. *Progress in Brain Research, Vol. 123: Peripheral and Spinal Mechanisms in Neural Control of Movement* (ed. M.D. Binder), pp. 247–257. Amsterdam: Elsevier. [Overview of the concept of CPGs in insects and snails.]

Wagner H. and Blickhan R. (1999). Stabilizing function of skeletal muscles: an analytical investigation. *Journal of Theoretical Biology* 199, 163–179. [Offers an approach to the application of the mechanical concept of self-stabilization on muscle function.]

Windhorst U., Hamm T.M., and Stuart D.G. (1989). On the function of muscle and reflex partitioning. *Behavioral and Brain Sciences* 12, 629–681. [Provides a survey concerning the function of muscle and reflex partitioning.]

Witte H. (2002). Hints for the construction of anthropomorphic robots based on the functional morphology of human walking. *Journal of the Robotics Society of Japan* 20(3), 25–32.

Witte H., Lesch C., Preuschoft H., and Loitsch C. (1995). Die Gangarten der Pferde: Sind Schwingungsmechanismen entscheidend? Federschwingungen bestimmen den Trab und den Galopp. *Pferdeheilkunde* 11(4), 265–272.

Witte H., Preuschoft H., and Recknagel S. (1991). Human body proportions explained on the basis of biomechanical principles. *Zeitschrift fur Morphologie und Anthropologie* 78, 407–423. [Functional morphology of the human body shape based on rigid body mechanics.]

Witte H., Recknagel S., Lesch C., Rao J.G., and Preuschoft H. (1997). Is Elastic Energy Storage of Quantitative Relevance for the Functional Morphology of the Human Locomotor Apparatus? *Acta Anatomica* 158, 106–111. [Proof for elastic energy storage in the locomotor apparatus of standing human beings.]

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