Can Robots Help to Understand Human Locomotion?

Können Roboter zum Verständnis der menschlichen Lokomotion beitragen?

Andre Seyfarth*, Sten Grimmer, Technische Universität Darmstadt,
Daniel F. B. Häufle, Universität Stuttgart,
Karl-Theodor Kalveram, University of Düsseldorf and Technische Universität Darmstadt

* Correspondence author: seyfarth@sport.tu-darmstadt.de

Summary As robots are becoming increasingly powerful and consequently potentially capable of reproducing human-like movements and interactions, the question appears how these motor skills found in biology could be transferred to the technical system. Such a transfer of biological movements to robots also offers the chance to question and to improve our understanding of the underlying principles on how movements are organized in nature. For this, a new conceptual framework, a test trilogy comparing human, simulation, and robot behavior will be presented and demonstrated exemplary.

▶▶▶ **Zusammenfassung** Mit der Entwicklung immer leistungsfähigerer Roboter können potentiell auch menschenähnlichere Bewegungen und Interaktionen realisiert werden. Dabei stellt sich die Frage, wie diese motorischen Fähigkeiten auf ein technisches System übertragen werden können. Eine solche Übertragung von biologischen Bewegungen auf Roboter eröffnet dabei auch die Möglichkeit, das Verständnis der zugrundeliegenden Prinzipien von Bewegungen in der Natur zu hinterfragen und zu verbessern. Hierfür wird ein neuer konzeptioneller Ansatz, eine Testtrilogie als Verhaltensvergleich von Mensch, Modell und Roboter, vorgestellt und am Beispiel demonstriert.

Keywords Biomechanics, locomotion, legged robots, computer simulation, test trilogy ▶▶▶ **Schlagwörter** Biomechanik, Lokomotion, Laufroboter, Modellierung, Testtrilogie

1 Introduction

Since the middle of the last century, computers have been developed which became increasingly powerful, lightweight, and user-friendly. High-level programming languages and graphical user interfaces helped to make programming more intuitive. Most recently, with introduction of tablet computers the usability was once more largely increased. These developments illustrate how technology can be developed to seamlessly integrate into our daily activities. A key to make these technologies more user-friendly was the invention of novel human-oriented technologies, like computer mice or touch-screens.

From an engineering point of view, one may ask: How can these technological advancements and state-of-the-art control theory be used to build robots, which can cooperate and interact with humans in a natural and intuitive way?

Over the last 50 years robots have been developed, which mostly operate separated from humans. Different to computing technologies, robots are still quite limited in their ability to interact with humans. Over the last decade highly advanced humanoid robots have been developed [1–3], which mimic the anatomic structure of the human body and have sufficient actuator and computing power. Still, these robots are mostly operated in isolation from humans in order to avoid unexpected interactions and potential injuries. In order to bridge this gap, more advanced motor skills of robots are required, which enable a direct interaction with humans in a meaningful way, like being capable of supporting humans in critical situations.

Coming from biomimetics that has in mind biological principles of structure and function, one may ask: How can these principles be converted into techniques and facilities for the design and engineering of robotic machines?

In order to achieve complex and dynamic motor skills it is not sufficient to develop more advanced control strategies, also the robot hardware and actuator design needs to be reconsidered. This is reflected in novel actuator designs such as variable impedance actuators [4]. As robots are becoming increasingly powerful and consequently potentially capable of reproducing human-like movements and interactions, the question appears how these motor skills could be transferred to the technical system.

Coming from biology, and having in mind manner and diversity of human behavior, one may ask: Can, starting from the available engineering techniques and computational facilities, a concept be derived, which explains human behavior?

The latter approach we call Inverse Biomimetics. Such a transfer of biological movements to robots also offers the chance to question and to improve our understanding of the underlying principles on how movements are organized in nature.

The three different approaches (coming from engineering, biomimetics, or biology) are, of course, intertwined which each other. Biomimetics, sometimes also called bioinspiration, requires a background of pure technical knowledge to identify a mechanism or functional principle in a plant or an animal, before transferring it into a technical application. The principles of animal or human motor control, however, are still hidden in a black box.

At the moment, we only can hypothesize known technical solutions as preliminary concepts. Regarding locomotion, instances of concepts currently discussed as underlying motor actuation are classical control versus diverse self-stability concepts with relaxed control effort. Inverse biomimetics than evaluates the chance, that such a concept is applied by the organism. In this regard, reduced 'conceptual robots' that are confined to express the function under consideration play an important role. The present article focuses on this inverse biomimetic approach, applies it to human locomotion in the framework of self-stability, and points out methods in pursuing it.

2 Test Trilogy – How to Compare Human Data, Simulation Models, and Robots?

Conceptual models can be used to describe experimental observations of biological movements and to identify the underlying mechanisms [5]. Usually the value of the conceptual model is estimated by a comparison of the predicted behavior of the model with the experimental findings. For instance, the bipedal spring-mass model [6] predicts walking patterns with two-humped patterns of the ground reaction force as a mechanically attractive, self-stabilizing[1] behavior based on compliant leg function. Such gait patterns are characteristic for human walking [7] but could not be predicted with other models before. Hence, under certain conditions the bipedal spring-mass model can predict body dynamics similar to human walking [8].

This similarity in body dynamics should not lead to the misleading conclusion that the human leg (or better the human body) would operate like a perfect spring during locomotion. Obviously, this is not the case as leg function clearly adapts to changes in ground conditions (e. g. walking up or down a slope, compliant or damping ground [9; 10]), a capacity a mechanical spring does not have. Hence, the spring-mass model only describes the overall behavior during walking or running, but not the origin of this behavior or its response to perturbations.

In order to test whether a model captures the fundamental function necessary to generate a desired movement it is therefore not sufficient to compare the similarity between predictions of the model with real data. Instead, the response of the movement to unexpected changes or perturbations must be included and compared in both experiment and simulation model. In the case of hopping in place, such a situation can be introduced by changing the ground level, e. g. by suddenly removing a block during flight phase (Fig. 1).

This example nicely illustrates the challenge of identifying the fundamental model describing the underlying mechanisms responsible for the response of the biological system to unexpected perturbations of the motion. The proposed models with different levels of complexity include representations of the mechanical level (segmentation, spring-damper elements), of the muscular level (muscle-tendon complex, activation dynamics) and of the neural level (sensory input, neural pattern generators, motor learning). Given that finally a sophisticated model is identified, which reproduces all responses to the perturbations reasonably well, is this sufficient to approve the model?

There are two key problems with this approach. First, the model might become so complex that all investigated perturbations are practically encoded in the model and the response to a new perturbation remains unclear. With this the predictive power of the model as a conceptual basis may be weak. Second, it remains unclear whether the model is represented in a realistic way, i. e. that it could function in real world. In order to prove this quality of the model, it is necessary to transfer the model to reality, i. e. to build the model in hardware. Hence, building a hardware copy of the model – a conceptual

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[1] Self-stabilizing walking (or running) behavior means that the gait pattern is not prescribed nor explicitly controlled but is the result of the intrinsic dynamics of the mechanical system based on proper combinations of leg stiffness and leg angle of attack.

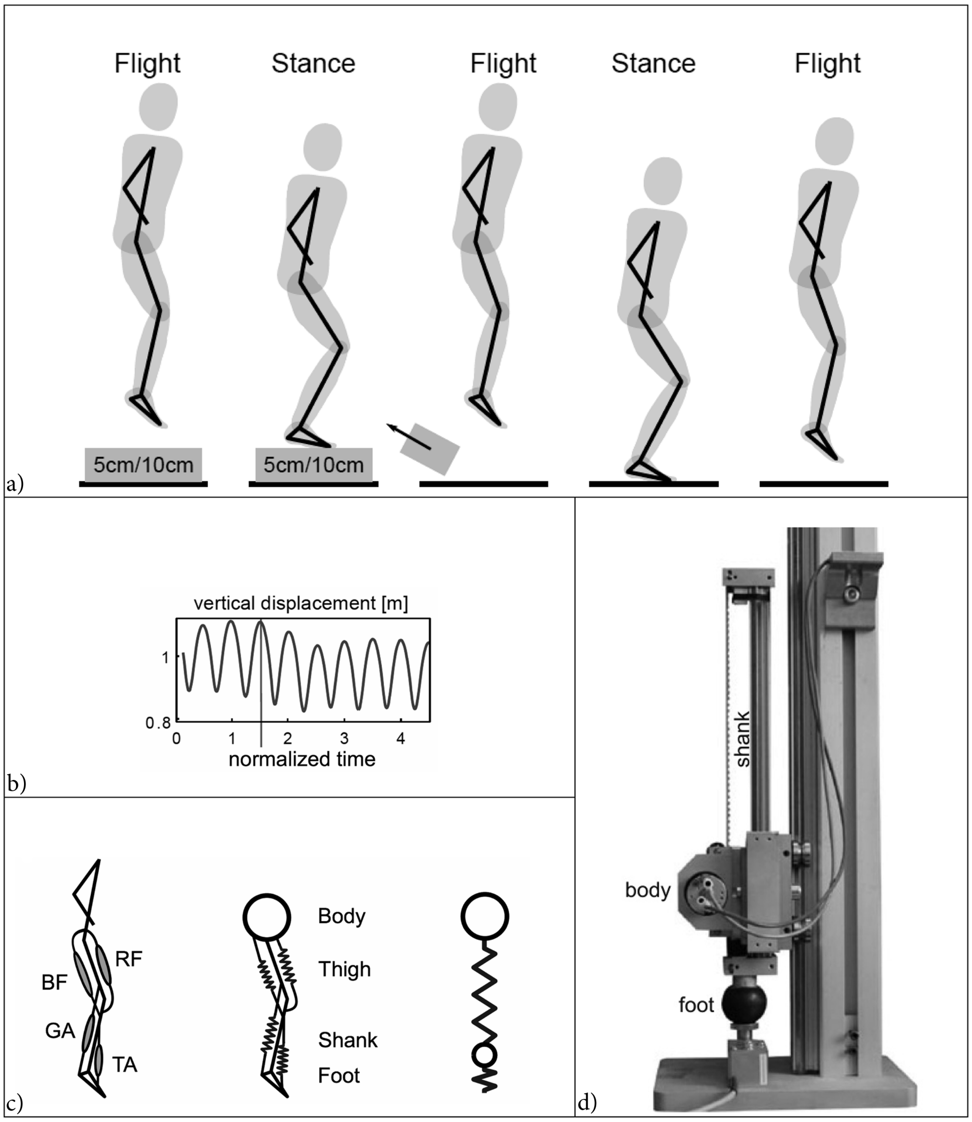

Figure 1 (**a**) Human hopping with changed ground level. (**b**) Displacement of the center of mass before and after perturbation (red vertical line). (**c**) Series of biomechanical simulation models with reduced level of complexity. BF, RF, GA and TA represent major leg muscles. (**d**) Hardware model MARCO hopper, an implementation of a one-dimensional hopping model. Adapted from [11].

robot[2] – can be used to prove the validity of an assumed movement strategy by comparison to experimental data and to predictions of the simulation model (Fig. 2).

Let us again consider the simple situation of human hopping in place. The same test procedure as described in Fig. 1 can then be applied to all three system levels (human, simulation, robot), which is illustrated in Fig. 2c. The response to a sudden change in ground level is shown in terms of a return map of two subsequent apex heights. After perturbation (step downwards in human experiments, step up or downwards described in the simulation model and realized in the robot platform), a steady-state apex height is reached within a few steps.

Depending on the outcome of the comparison of human, simulation and robot behavior, a more detailed representation of the biological system may be required. For instance, a simple mechanical spring cannot explain adaptations to changed ground level during hopping. Instead, energy-stabilizing mechanisms need to be represented in the conceptual model. This can be done at the mechanical level (e. g. by energy supply during ground contact, by introducing damping or changed leg spring parameters, see [11] and [13]) or by taking neuro-muscular mechanisms into account [9]. Based on spring-like leg behavior, stable hopping (i. e. a desired hopping height) can be achieved by a combination of increasing rest length of the spring and decreasing stiffness of the leg spring.

When adding damping in parallel to the leg spring, not only decreases but also increases in leg stiffness dur-

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[2] The term "conceptual robot" is used for a hardware model as part of the test trilogy, however such research systems like the MARCO hopper may not comply with current definitions of a robot (e. g. http://definitions.uslegal.com/r/robotics/).

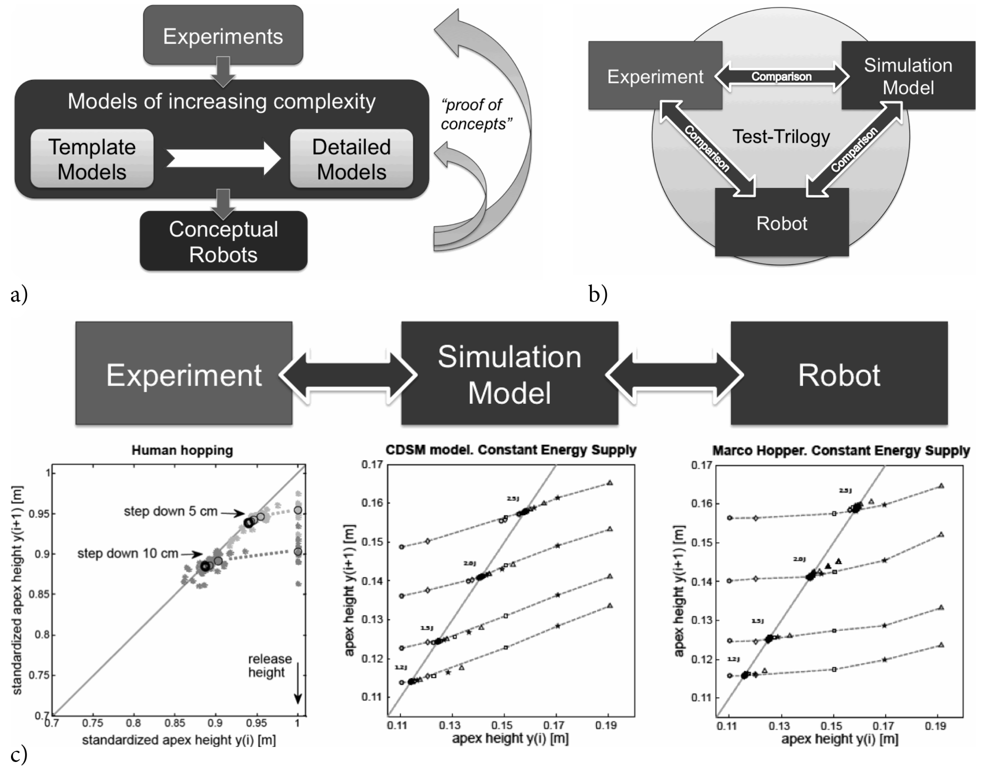


Figure 2 (**a**) Conceptual robots may provide a research tool to prove the practicability of the movement strategies motivated by simulation models of different levels of complexity. (**b**) The comparison of the robot, simulation and human behavior (test trilogy) provides a tool to prove the practicability and the validity of the concept [12]. (**c**) Example of the test trilogy applied to human hopping with different unexpected changes in ground level. The hopping height $y(i+1)$ after one step is plotted vs. the height of the previous apex height $y(i)$. Adapted from [11].

ing contact may result in stable hopping [13]. This is different to the case of an ideal leg spring without damping, where only decreases in leg stiffness (in conjunction with increases in rest length of the leg spring) resulted in stable hopping.

The results in Fig. 2c show that even though all three systems (human, model, robot) show stable hopping patterns, clear differences in the return map between the different conditions are present (for details see [11]). It is important to note that the test trilogy described here does not guarantee that an identified movement concept is correct but it clearly disqualifies concepts in a more systematic way then before, e. g. by simply comparing the unperturbed behavior predicted by simulation models with human experiments.

3 From Mechanical to Neuro-Muscular Models

Spring-like leg operation is a common feature in legged locomotion and can be observed in hopping [15], running and walking [16]. This motivates the description of the dynamics of the body with the help of conceptual spring-mass models [3; 17]. Even though these models may predict the center of mass (COM) trajectories reasonably well [8], they cannot predict how to compensate for changes in system energy as described above (Figs. 1, 2c). In the human body, spring-like leg behavior can only be achieved by active muscle function, which is required to generate the experimentally observed patterns of the ground reaction forces. A simple strategy could be to activate the muscles such that the work would be mostly done by elastic stretching and shortening of the tendons, which are attached in series to the muscle [13]. Such a strategy can be indeed found in animals with long tendons, like in horses [19]. Here the muscle fibers mainly damp oscillations, which occur due to the landing impact. The situation is different in human locomotion, where muscle fibers clearly contribute to the work of the muscle-tendon complex [20]. In fact, spring-like leg function could even be mimicked without any compliant tendons by a proper activation of the muscle fibers. But how can a matching muscle activation pattern be obtained?

One possible solution would be to find an appropriate activation pattern by optimization. For instance, muscle activation can be optimized for achieving maximum hopping height in a segmented leg model [16]. Such patterns could be generated with the help of central pattern generators [22].

Another strategy would be to use proprioceptive signals to modulate the neural stimulation to the muscle. For this different sensory signals (e. g. muscle force, fiber length and velocity) could be used, whereas force signals and length signals provide the additional advantage of energy stability such that changes in ground level can be compensated [9; 21].

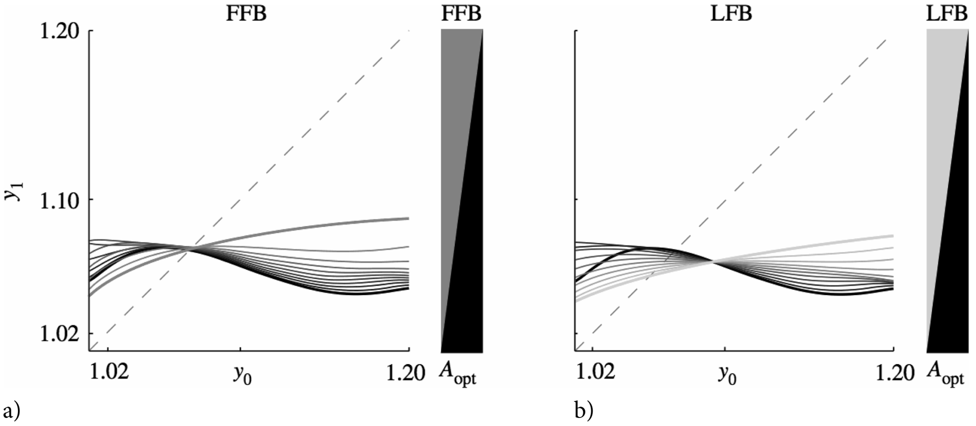


Figure 3 Stability analysis of hopping using a return map of the apex height $y_1 = f(y_0)$. Hopping with a combination of (**a**) force feedback (FFB) and optimal predefined activation pattern and (**b**) of length feedback (LFB) and optimal predefined activation pattern can increase the stability against energetic perturbations (after changed apex height y_0, to the same apex height y_1 is approached within a few hops). Adapted from [9].

The results mentioned above rely on the Hill-type model of muscle fibers, namely the force-velocity relationship [18]. Simulation studies showed that a combination of a predefined pattern with sensory inputs might lead to an enhanced rejection of energy perturbations [9] (Fig. 3). These results indicate that the neuro-muscular system can be fine-tuned to compensate for energetic disturbances by a combination of feedforward signals modulated by sensory inputs. It remains to investigate how such mechanisms are implemented at different joints and muscles within the human body.

One successful implementation of a combination of proprioceptive pathways in a three-segmented leg was provided in a simulation study of human walking [23]. The model was able to demonstrate walking gaits with human like muscle activation patterns of seven major muscles per leg, which were able to adapt to slightly changed ground levels (walking small steps up and down). Hence, a network of sensory inputs could realize the modulation of muscle activation during walking on uneven ground while relying on the beneficial properties of muscles [9; 24] and the mechanics of the segmented body [25].

4 Elementary Functions Required for Legged Locomotion

The neuro-muscular mechanisms described in the last section provide evidence that cyclic movements leading to spring-like leg behavior (e. g. hopping in place or walking) can be generated using simple feedforward signals or sensory inputs (proprioceptive pathways) by taking advantage of the properties of the muscular (e. g. Hill-type muscle function, compliant tendons) and the mechanical system (e. g. leg segmentation, joint stiffness). Spring-like leg function provides advantages for locomotion as it contributes to the cyclic stability of walking and running [6; 19]. However, besides spring-like leg function, other fundamental requirements must be fulfilled for successful locomotion.

Legged locomotion, such as human walking and running, can be considered as a synthesis of three elementary functions, which are realized in parallel:

1. axial leg function, i. e. the ability to generate sufficient force in leg axis for rebounding against gravity during contact,
2. rotatory leg function, i. e. the ability to generate a pendulum-like movement of the leg swinging forward (leg protraction) and backward (leg retraction), and
3. body alignment, i. e. the ability to keep the trunk in a certain orientation, e. g. upright in human walking.

These three functions require an appropriate interplay between body mechanics, actuator dynamics and neural control including sensory inputs and feedforward schemes. Each of these elementary functions can be realized in different ways, mechanically or by neuro-muscular control. In the previous sections, the focus was on the axial leg function. This represents the ability of the body

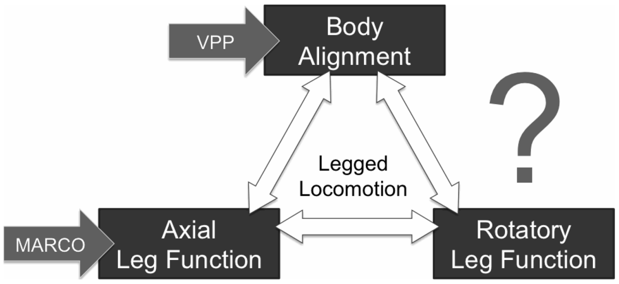


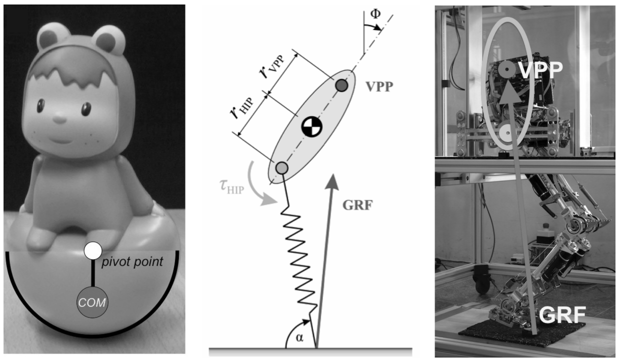
Figure 4 Three fundamental functions enabling legged locomotion. Body alignment (body posture) results in an approximately constant trunk orientation with respect to gravity and can be achieved with the VPP concept. Axial leg function describes the ability to withstand gravity by generating sufficient upward momentum during ground contact (e. g. by spring-like leg function) and was investigated with the MARCO Hopper (see Fig. 1d). Rotatory leg function comprises the ability of the leg to propel itself forward (leg protraction) and backward (leg retraction) relative to the body in preparation of the next ground contact. These three functions need to be integrated in order to achieve stable locomotion like human walking and running.

to develop interaction forces along the leg axis, pointing from the contact point (center of pressure on the ground) to the body center of mass (COM). However, also non-axial forces may be required at certain conditions, e. g. to modulate forward progression [27]. In the following section, we will provide additional insights on how postural stability could be realized during locomotion.

5 Keeping the Trunk Upright During Locomotion

In legged locomotion, the main task is to move the body in a desired direction. At the same time, the trunk stays oriented with respect to the ground. To achieve this postural alignment, restoring torques are required to counteract a perturbation in trunk orientation. In human locomotion, this could be realized by measuring the trunk orientation (e. g. with the help of vestibular or visual information) and by applying a feedback control scheme (e. g. PD control). Alternatively, also proprioceptive information from leg muscles could support upright body orientation [28]. Consider the case that the orientation of the trunk cannot be directly measured or that this information is distorted (e. g. due to a vestibular disorder). Is there an alternative to keep the trunk aligned in a certain orientation with respect to the ground? Is there any mechanical strategy to solve this problem?

Let us consider a simple mechanical toy, the roly-poly toy (Fig. 5a). Here the spherical shape of the lower body results in a pivot point (center of rotation) above the center of mass (COM). In the case of a perturbation from the vertical position, the COM is lifted as it rotates around the pivot point and the body responses similar to a pendulum. Consequently, the COM oscillates around the neutral position (COM directly below the pivot point) until the resting position is reached. It is important to note that a mechanical pendulum does not provide an asymptotic stable resting position without damping. Still it provides natural stability, which can easily be transferred into asymptotic stability (e. g. using damping).



a) b) c)

Figure 5 The VPP concept. (**a**) Self-stable upright body posture in the purely mechanical roly-poly toy. (**b**) Transfer of the pivot-point idea to a conceptual VPP model based on the spring-mass model extended with a rigid trunk (Maus et al., 2010). (**c**) Application to humanoid robots, like the BioBiped robot. In order to achieve an upright trunk posture (body alignment, Fig. 4) during locomotion, the direction of leg force needs to be controlled during the contact of the segmented leg while preserving the axial spring-like leg function. Picture provided by Christophe Maufroy.

Here we are interested if this idea of creating a virtual pendulum can also be applied to legged locomotion. For this we extend the spring-mass model with an upper rigid body (Fig. 5b) and deviate leg force to a virtual pivot point (VPP) by applying the corresponding hip torque. This simple hip control scheme can provide postural trunk stability in both walking and running [29]. The hip torques predicted by the VPP model are similar to those observed in human walking with extending hip torques at the first half of stance and hip flexion torques after midstance. In the VPP model, the amount of hip torque depends on merely two sensory inputs: the amount of leg force and the orientation of the leg with respect to the trunk. This information can be derived based on sensory signals in legged robots, such like the BioBiped robot (Fig. 5c). The VPP-based control of trunk orientation may reduce the dependency on supraspinal pathways based on vestibular or visual information. As a result, the trunk becomes oriented vertically without the need to measure the direction of gravity or the horizontal ground. This also permits the use of the trunk as a reference for rotational leg control (e. g. leg orientation at touch-down, [26]). The hip torque patterns predicted by the VPP model may not only provide postural trunk stability but may equally support rotatory leg function (Fig. 4), i. e. swinging the legs fore- and backward during locomotion.

6 Closing the Reality Gap of Bioinspired Conceptual Models

Most of the conceptual models described above were derived based on experimental findings on human or animal locomotion. For the sake of simplicity, these models are focused on specific aspects of legged locomotion but fail in describing the function of the human body as a whole. In order to transfer these concepts into a technical application (biomimetics approach) it is required to identify a mechanism or functional principle in a plant or animal. Regarding biological movement control, we cannot yet identify such a principle, but we can infer a technical solution via the test trilogy, described in Sect. 2. This is called *inverse biomimetics*. With this, conceptual models can be evaluated regarding their ability to provide a solid and realistic basis for more complex and integrative models for human locomotion.

Without the help of *hardware models* the ability of simulation models to describe the biological system is limited, as the concept might not withstand the reality-check. This may even be the case if the conceptual model predicts similar behavior as the biological counterpart. The validation of concepts by hardware demonstration provides a valuable tool to question the limitations of conceptual models. The hardware model (conceptual robot) shares important features with the conceptual model, namely to be *synthetic*, i. e. a forward dynamic model, and to be *conceptual*, i. e. based on well-defined assumptions. At the same time, the hardware model also shares an important property with the biological system, namely to be *realistic*. The combination of these features (being conceptual and being realistic) provides the basis that hardware models may become a valuable research tool to support the research on legged locomotion [14].

7 Conclusions – From Conceptual Robots to Multi-Functional, Human-Oriented Robots

The here described research framework aims at developing more functional and more realistic conceptual models inspired by movements observed in nature. For this approach, conceptual robots (hardware testbeds) need to be developed in order to validate and guide the design process. As an ultimate goal, this will lead to a hierarchy of conceptual models based on a few underlying template models [5]. Such a concept-driven model design process will help to question and enhance our understanding of the organization of human and animal movements. At the same time, this approach can also guide the design and construction process of a novel generation of bio-inspired and concept-driven robots. This process does not aim at mimicking a specific movement pattern of a given biological counterpart but at synthesizing movements based on identified and hardware-proved underlying principles of these movements. Bases on these principles the functional space (parameter set) to access a desired class of movement (e. g. legged locomotion) can be defined.

For this goal, the mechanical and actuator design of the robots must comply with these principles. This requires an iterative design process comprising system mechanics (including the environment), actuator dynamics and control with increasing levels of complexity and integration, starting with simple systems. For this, new hardware and software technologies are required to support the concept-driven engineering process. Based on current technologies, movement strategies (e. g. for locomotion) cannot easily be applied or extended to different body morphologies or more complex movement tasks. The used control schemes are often hardware-specific, require fast signal processing and highly precise sensors.

In order to achieve this, multi-functional evaluation tools and procedures for movement analysis need to be developed in order to prove the functional similarity at different levels (e. g. human, simulation and robot behavior) during steady state and non-steady movements, which may be provoked by well-defined perturbations (e. g. changed ground properties, [30; 31]).

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Prof. Dr. Andre Seyfarth is professor for Sports Biomechanics at the Technische Universität Darmstadt and head of the Lauflabor Locomotion Laboratory. This research group was founded at the University of Jena in 2003 within the DFG Emmy-Noether young investigator excellence programme. Research interests: human and animal movements, conceptual models in computer simulation and hardware testbeds.

Address: Lauflabor Locomotion Lab, Institut für Sportwissenschaft,
TU Darmstadt, Magdalenenstr. 27, 64289 Darmstadt,
e-mail: seyfarth@sport.tu-darmstadt.de

Dr. Sten Grimmer is a postdoctoral researcher at the Lauflabor Locomotion Laboratory since 2007. Research interests: mechanisms of obstacle avoidance, feedback mechanisms, quiet human stance.

Address: Lauflabor Locomotion Lab, Institut für Sportwissenschaft,
TU Darmstadt, Magdalenenstr. 27, 64289 Darmstadt,
e-mail: sten.grimmer@uni-jena.de

Dipl. Phys. Daniel Häufle is a PhD student at Computer Simulation of Human Movement research group at University Stuttgart. Research interests: theoretical muscle modeling (macroscopic level), proof of theoretical concepts in physical/technical/robotic experiments.

Address: Human Movement Simulation Lab, University of Stuttgart,
Department of Sport and Exercise Science, Allmandring 28, 70569 Stuttgart, e-mail: daniel.haeufle@inspo.uni-stuttgart.de

Prof. Dr. Karl-Theodor Kalveram is professor for Cybernetic Psychology and Psychobiology at the University of Düsseldorf and visiting professor at the Lauflabor Locomotion Lab at the Technische Universität Darmstadt. Research interests: sensorimotor control of speech and stuttering, sensorimotor control of trunk and limb movements, effects of noise on men in an ecological perspective.

Address: Lauflabor Locomotion Lab, Institut für Sportwissenschaft,
TU Darmstadt, Magdalenenstr. 27, 64289 Darmstadt,
e-mail: kalveram@uni-duesseldorf.de