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Intelligence by mechanics

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Research on the biomechanics of animal and human locomotion provides insight into basic principles of locomotion and respective implications for construction and control. Nearly elastic operation of the leg is necessary to reproduce the basic dynamics in walking and running. Elastic leg operation can be modelled with a spring-mass model. This model can be used as a template with respect to both gaits in the construction and control of legged machines. With respect to the segmented leg, the humanoid arrangement saves energy and ensures structural stability. With the quasi-elastic operation the leg inherits the property of self-stability, i.e. the ability to stabilize a system in the presence of disturbances without sensing the disturbance or its direct effects. Self-stability can be conserved in the presence of musculature with its crucial damping property. To ensure secure foothold visco-elastic suspended muscles serve as shock absorbers. Experiments with technically implemented leg models, which explore some of these principles, are promising.

Keywords: walk; run; biomechanics; stability; segmentation; impact

1. Introduction

This article focuses on research pushed forward in recent years in the group of Motion Science and the Locomotion Laboratory at the Friedrich-Schiller-University of Jena.

In the animal kingdom, motion and behaviour can be considered synonymous. A special form of motion, locomotion, allows the creature to change place and is essential for example for foraging, escape and courtship. Even in the human species, which has amplified its locomotor abilities by technical devices, the basic abilities to crouch, walk, run and climb remain crucial. For example, in sports, extreme performances of locomotion are expressed. Impairment of locomotion owing to injuries can inflict dramatic restrictions to the quality of life. Compensating measures keep a growing medical industry busy. Enhancing our conceptual understanding of locomotion thus has far reaching basic and applied consequences. In particular, it may help to transfer knowledge into engineering and improve performance of technical legged systems.

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One contribution of 15 to a Theme Issue ‘Walking machines’.

Experimental and theoretical investigations of locomotion have a long tradition. The advance in measuring techniques such as the development of high-speed cinematography based on infrared video, the design of electromechanical devices to measure the ground reaction force (force plates) and diminutive amplifiers for electromyography has made gait analysis a standard method in clinics and research institutes. This is accompanied by advances in data processing that have been made possible by microelectronics. Both improved measurement techniques and the possibilities for numerical analysis have advanced our understanding of locomotion and allowed many insights with respect to the design and function of the musculoskeletal system. Nevertheless, the limited movement abilities of walking machines and the limited performance of computer simulation models can be taken as hints that our understanding of human (and animal) legged locomotion still has essential gaps. We try to close some of them combining experiments on human subjects and technical leg models with simulation studies.

Some questions elucidated in our groups have been: can we understand the walk–run transition based on mechanical principles? What are the rules for segmentation of the legs? Can we elegantly cope with uncertainties connected with a rough environment and in construction and control? How should we cope with the essential bumpiness of legged locomotion? What properties should an actuator have to suit legged locomotion? It is the goal of this article to communicate some basic ideas we developed about principles of walking and running, and to explain their implications on global properties, geometries and control of legged systems. Especially the issue of stability and running across rough terrain will be addressed. The relevance of this topic in the context of the construction of walking machines will be accentuated throughout the article.

2. The quasi-elastic template for walking and running

Using spring-like operation of the leg allows dynamically correct locomotion and change of gaits by continuously increasing system energy and global parameters. It further helps to generate a smooth ride. With respect to control, the elastic leg may be used as template and anchor.

A template is a simple general model that serves as a guide for control (Full & Koditschek 1999; Full *et al.* 2002). In systems with many degrees of freedom, control becomes ambitious. This is one of the reasons why the control of walking machines is more demanding than the control of a helicopter. Engineers tend to collapse the degrees of freedom to make control possible and transparent (comp. Pfeiffer 2005). If you turn to the right, you do not think about the rotations of the propelling motor, you rather may think in terms of the turning wheel. Similarly, legged systems demand for suitable control-corresponding simplifications. During running across a path blocked by obstacles you like to place your foot, but you do not think what your knee or your ankle joint should do to provide for such a placement. Searching for templates is therefore not just a simplified way to do mechanical modelling; it may turn out to be essential to the understanding of central control 'algorithms' and central representations. A template which entails kinematic features as in the example of the foot placement is useful. Corresponding central codes have been identified (Georgopoulos *et al.* 1993). In dynamic behaviour typical for locomotion, templates which entail general dynamics of a system may be even more useful. The global system can be steered by changing global parameters. On the other hand, the model provides an anchor for local properties. They should be adjusted to assure efficient global parameters (Full & Koditschek 1999).

In the 1960s and 1970s, processing of force plate data revealed that the energetic fluctuations of the centre of mass of walkers and runners can be described by two simple mechanisms (Margaria *et al.* 1963; Cavagna *et al.* 1964, 1977). During walking, potential and kinetic energies change largely out of phase leading to the idea of the inverted pendulum: a stiff stance leg topped by a point mass. We will return below to the fact that stiff-legged walking entails a serious flaw as it cannot be used to correctly predict the general time course of the ground reaction force, the footprint of global dynamics. Nevertheless, even a compliant leg can display extended periods, in which exchange between potential and kinetic energy dominates. During running, fluctuations in potential and kinetic energies occur in phase. The corresponding model is a spring topped by a point mass, i.e. a spring loaded inverted pendulum. Here, the model describes the time course of the ground reaction force rather well (Blickhan 1989; McMahon & Cheng 1990). Instead of relying merely on stepping patterns, gaits now were increasingly defined by the basic dynamic mechanisms. The simple models facilitate general insights. For example, during running, a certain combination of leg stiffness and angle of attack is necessary to describe experimental data for a given body mass and leg length. More detailed models including segmentation or even soft tissue must lead to similar general dynamics. It has been intriguing to find that small ‘trotting’ insects decelerating with the front legs and accelerating with the hind legs still use the same global mechanism (Full *et al.* 1991; Blickhan & Full 1993; Farley *et al.* 1993). The legs cooperate to form a virtual spring effective in the sagittal as well as in the frontal plane. Despite their small size they bounce. Roughly they use a similar dimensionless stiffness as large vertebrates do (Blickhan & Full 1993).

With the advent of passive walkers (McGeer 1990, 1992, 1993; Coleman *et al.* 1997; Coleman & Ruina 1998; Garcia *et al.* 1998; Ruina 1998; Coleman *et al.* 2001) and hopping machines (e.g. Raibert 1986; Altendorfer *et al.* 2001; Saranli *et al.* 2001), descendants of such simple models were successfully transformed into legged machines. In fact, elastic hoppers still hold the speed record of legged robots and passive walkers are certainly most efficient.

However, the passive strategy seems to limit the behavioural variation. In locomotion, the simplest variation in behaviour consists in alteration of the speed of locomotion. In light of the preceding paragraphs, this, at the same point, implies changing gait or the basic mechanism of locomotion. Correspondingly, designers of legged machines attempt to implement essentially different algorithms and controls for slow and high speeds. In animals, it appears as if the character of the control is changing too with speed with a dominating feedback control for slow speed and a control which more relies on feed-forward at high speed. On the other hand, so far there is no evidence for a switch in the central control while changing speed and gait. In addition, so far no detailed forward model can be driven from walking to running just by opening the throttle as seems to be the case in nature (Shik *et al.* 1966). Simple dynamic models, and maybe templates, are needed which incorporate the basic features of both walking and running. Stiff-legged running is not possible. However, it is

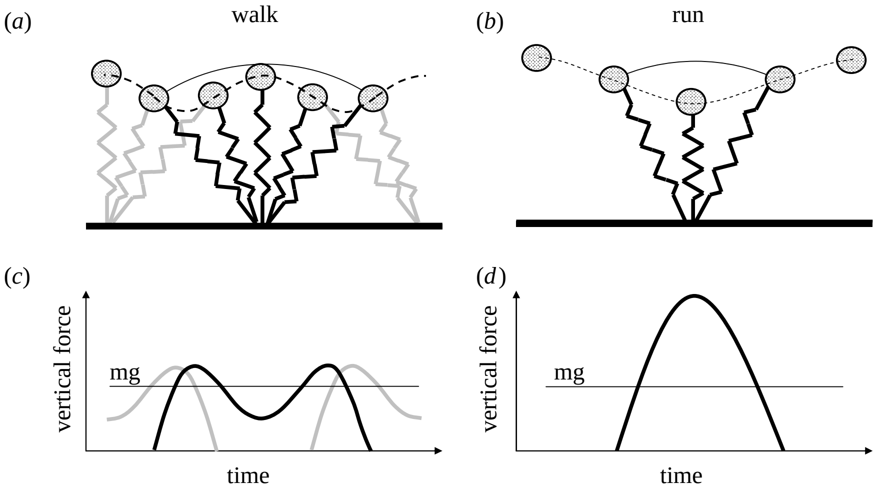

Figure 1. The spring-mass model for walking (*a*, *c*) and running (*b*, *d*) during a single contact from apex to apex. (*a*, *b*) Path of the centre of gravity (dashed lines) and springy legs in contact (black right leg, grey left leg). In walking, the leg extends during midstance and almost approaches its initial unloaded length (thin line). (*c*, *d*) In walking the typical camel-back pattern of the ground reaction force is obtained. The walk depicted represents a rather dynamical stable mode (comp. Geyer *et al.* 2006).

possible to introduce compliance into a walking leg (figure 1). This seems to be a nuisance at first glance as the stiff leg with a locked knee seems to save energy. However, the stiff-legged walker has to pay for the losses at touchdown (e.g. McGeer 1992). In contrast, a walker using a massless elastic leg would not face such losses. In animals, quasi-elastic leg operation is maintained by steering muscle tendon complexes and does not come for free. A quantitative comparison of the cost is not available so far.

The use of an elastic leg during walking has been addressed several times (e.g. Lee & Farley 1998), but no formulation has been successful in describing that the typical camel-back pattern of the vertical ground reaction force and the typical double support both characterize walking. It turned out that a simple expansion of the spring-mass model can provide a very successful description of both features (figure 1; Geyer *et al.* 2006). In fact, it is simply necessary to include the double support in a correct manner. Let us consider a complete stance phase including compliant legs and double support. At touchdown of the considered leg (let us say the right one), the load of the body mass is still partially supported by the left leg. With compression of the leg spring, the load is taken up gradually by the right leg and the left leg is unloaded. This dynamic loading results in a first force peak. While the leg continues to rotate, the spring-mass system starts to oscillate thereafter, first unloading and then loading the spring again. During the second peak, the left leg is set to the ground and unloads the right spring. During walking and running at similar speeds, a rather similar vertical stiffness is used (figure 2). However, vertical stiffness should not be confused with leg stiffness, the similarity merely indicates that in both gaits fluctuations in vertical displacement are proportional to those in the vertical ground reaction force.

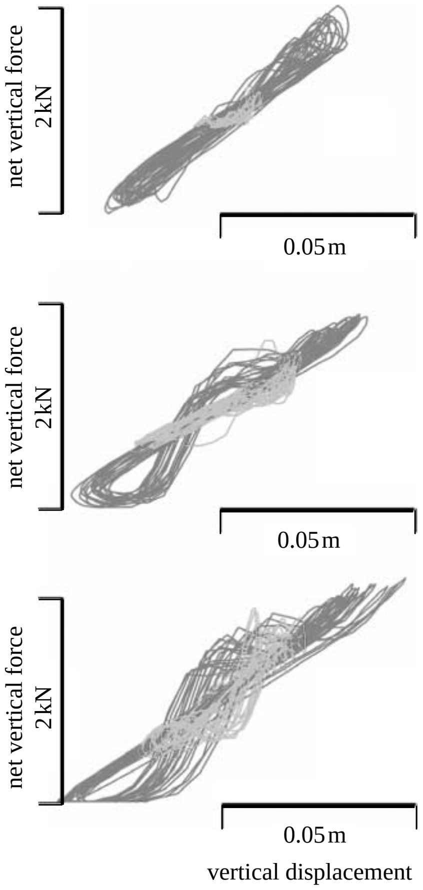

Figure 2. While walking (bright) and running (dark) at different speeds (from above: 0.25, 0.75 and 1.25 mean transition speed), vertical stiffness as the average slope of the characteristics of the vertical force depending on the vertical centre of mass displacement represents a rather conservative property and is independent of the selected gait. Differences are observed with respect to energy occurring in discrete steps. The measurements are obtained for an individual running on an instrumented treadmill (ADAL 3D, Tecmachine) in the Locomotion Lab at Jena.

Introduction of leg compliance results in a fair description of the patterns of ground reaction force observed during walking.

By successfully applying the spring-mass model to both walking and running, gait transitions can be evoked by changing the system energy and/or adjusting the compliance and the angle of attack of the leg (or by changing gravitation). The transition speed is traditionally conceived to be determined by the fact that the centrifugal forces increasing with speed of locomotion would drive the system off ground for fast pendulum-like walks. This concept has led to the use of the Froude number (Fr, used in fluid dynamics to describe the ratio between kinetic and potential energies) to compare speeds of animals of different size. A transition from walking to running is assumed to occur at $Fr=1$. However, measurements indicate that animals prefer to change gait at $Fr=0.4$ (Thorstensson & Roberthson 1987). Walking is not characterized by a pure inverted pendulum motion but the path is modulated by the ringing of the mass around the landing height. Now, the argument of taking off owing to the centrifugal force loses significance and the trajectory becomes almost flat. Compliant walking can be considered as an efficient method to achieve a smooth ride. A completely flat ride can be conceived as a transition point from walking to running. We can calculate the speed where the trajectory of the centre of mass during running becomes nearly flat. Analytical approximations revealed that this speed scales with the Froude number which is close to 0.4 (Geyer *et al.* 2005).

In robotics, a smooth and flat ride of the centre of gravity is a movement goal. An enforced smooth ride at each instant is costly, results in high torques at the hip and does not take advantage of the global dynamics of the system. Legs with sufficient compliance would result in a rather smooth walking and running. They would be suitable for both gaits and the gait transition could be achieved without a general change in control.

3. Consequences of segmentation

Copying human segmentation in a humanoid robot is of advantage with respect to energy and structural stability. In addition, it seems to be essential for the control of gaits.

(*a*) *Movement of the segments during walking and running*

Despite the similarity of global leg properties, the kinematics of the segmented leg differs during walking and running.

Nature did not introduce telescope legs. This avoids long gliding distances which might be cumbersome for soft tissue, innervation and supply with nutrients. Furthermore, segmented legs have advantages also in the context of an environment with obstacles and with respect to variability in behaviour. Think about climbing a tree with telescope arms and legs. This multi-purpose context remains for future investigations. Here, we concentrate on locomotion on level ground. Whereas quadrupeds and insects can afford to stand and walk on the tips of their legs, we need the foot segment to balance our body in the frontal area. This turns out to be a rather dynamic process, the centre of gravity is swaying in close to random motions continuously around the centre of the base of support defined by 1 or 2 ft. Latest results show that fluctuations are not restricted to the ankle joint but are scattered over all major leg joints with amplitudes up to 0.3° and frequencies from 0.1 to at least 10 Hz (Günther *et al.* submitted). Movements of the segments are already visible during quiet standing. The classic picture of stability by keeping the vertical projection of the centre of gravity within the polygon of support is still valid. However, the fluctuations seem to be an expression of multi-segment dynamics necessary to cope with non-stationary properties of the neuromuscular system.

During walking and running, the picture of static stability is only of limited use. Here, asymptotic stability does not provide a safeguarding background. We purposefully move the vertical projection of our centre of gravity outside the centre of support, which introduces a falling movement. The fall is prevented by placing the next foot in time on the right spot. Correspondingly, the foot loses its significance for maintaining stability and its role must be seen in the context of the whole leg.

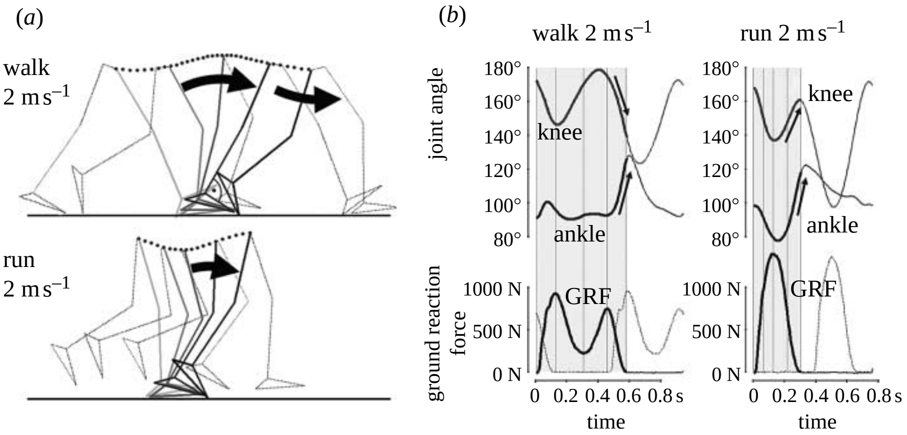

Figure 3. Kinematics of the segmented leg while walking and running at 2 m s^{-1} on a treadmill. (*a*) Stick-figures; (*b*) time course of the knee and ankle angle and of the vertical component of the ground reaction force (GRF). In walking, knee flexion prolongs leg retraction at the early and late stance phases (Seyfarth 2005). Similar joint kinematics are found in the bipedal robot (figure 8).

By placing the foot with its heels and shifting the point of pressure towards the toes, the foot acts like the rim of a wheel. Owing to the eccentric positioning of the ankle joint and the action of the M. tibialis anterior, its placement helps to bend the knee in the first quarter of stance. It starts to extent until reaching midstance, where the stiff inverted pendulum situation is approached. With the progression of the centre of gravity the knee again starts to bend, i.e. the protraction of the thigh starts already during the last third of the stance phase (Seyfarth 2005). During the last quarter of the stance phase, the heel is lifted off the ground owing to ankle extension (Saunders *et al.* 1953). At midstance, in walking, ankle and knee operate in a push–pull situation. In contrast, during running both joints are working in phase, the coupling between the movement of the ankle joint and the knee joint is increasing. At the preferred transition speed, the hip moves in both gaits in a close to sinusoidal pattern with a short interruption of leg retraction owing to landing impact (figure 3). During running, the role of the foot as a rim diminishes, whereas its role as spring segment increases.

Similar roles may be attributed to the joints and segments of all legs of mammals operating in the sagittal plane. However, the pattern of loading changes with size. Small animals most frequently decelerate with their front legs and accelerate with their hind legs (Witte *et al.* 2002), which should affect the action of the different joints and segments. This difference among legs becomes most prominent for legs in arthropods such as insects (Full *et al.* 1991) where each pair has a different role and the joints and segments are loaded differently.

(*b*) *Leg segmentation and effective mechanical advantage*

Specific segmentation and segment orientation complement one another to reduce cost of force generation in a shortened leg.

Investigations which present a rationale for the layout of the segments and joints in the context of locomotion are rare. Is the foot length determined by the requirements of standing or are there different aspects coming into play?

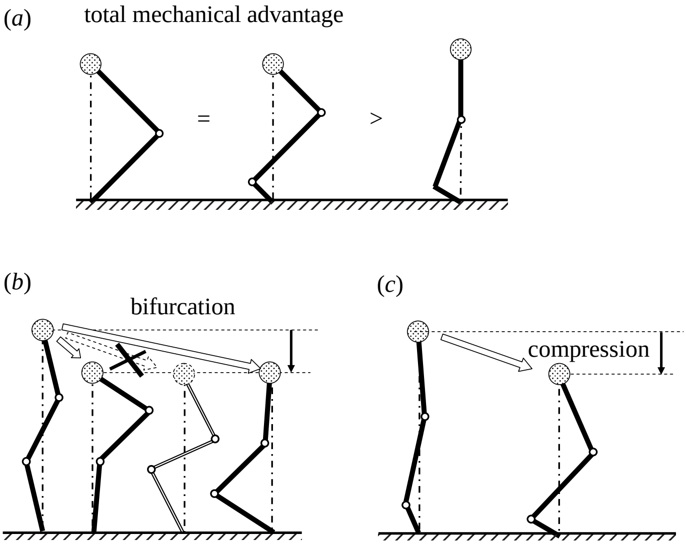

Figure 4. An effective foot with a length of 0.4 thigh length is optimum with respect to low energy leg shortening and helps to avoid structural instability. (*a*) As compared with the three-segment equivalents of a two-segment leg, the aligned configuration with a short foot has a higher effective mechanical advantage. (*b*) When compressing a symmetrically configured leg with elastic joints a structural instability is observed. (*c*) A short foot helps to move the point of bifurcation out of the working range of the leg.

Is it, for example, also advantageous to use the human leg geometry during running? By using the sum of torques necessary to maintain the ground reaction force pointing from the contact to the hip, we introduce a simple cost function which may also be relevant for robotics. During the stance phase of a human runner, leg masses are negligible. We will address the consequences of leg mass below. In this case, a quasi-static approach can be taken. It is also necessary to consider basic conditions a human leg is facing. Such a condition is that the heel should not dig through the surface. Furthermore, we consider the leg as being compliant.

The first question may be why not use a two-segment leg. We can always find a corresponding three-segment configuration and this configuration is not the one with minimum torque (Günther *et al.* 2004). It turns out that such configurations can always be topped with a higher effective mechanical advantage by asymmetric configurations where the two joints have different angles. In other words, the two-segment leg is more expensive to drive than carefully selected asymmetric three-segment configurations. Or to express it differently, using similar muscle force and lever arms the three-segment limb can produce higher axial forces (figure 4; see also Alexander 1995).

It is of advantage to have a foot during locomotion. This foot should not be straightened and should have the relative length our foot has. The gain with respect to the two-segment leg is highest with a shank of about 0.45 relative leg length and a ratio between foot and thigh length of about 0.4. In fact, such a leg has an optimum compression at about 6% of its length, which is close to the value observed during the stance phase in human locomotion.

The statements above are valid for humans and large animals where the advantage of the potential of acceleration is traded for a reduction in the cost of locomotion. For small animals, acceleration is crucial and they typically come along with bent legs. There, legs with segments of about equal lengths provide a solution with diminished cost, even though, as compared with the straight position, the advantage is strongly reduced. For legs shortened to about half the maximal length, crouched situations with the proximal joint below the distal joint can be suitably explored giving equally segmented legs another advantage. It should be noted that these results are bound to the assumption that the ground reaction force points to the hip. For small animals, this is not the case and different geometries might be preferable (Fischer & Blickhan 2006). This is especially true for situations where legs work against each other. There, all geometries of the legs on the ground must be considered simultaneously in the optimization process (Full *et al.* 1991).

(*c*) *Structural stability*

Segmentation and orientation influence structural stability of the segmented leg.

The preceding considerations are static in nature and do not take energy, i.e. the instantaneous combination of force and displacement, into account. As segmentation introduces local nonlinearities, the relationship between leg shortening and energy can become rather complicated. To predict changes in energy, information about the joint torques in relation to joint rotation must be available. This can be achieved by introducing revolute joint springs. Thereby, transparency and simplicity are maintained. In such a leg, the joints in series yield under load until equilibrium is reached. In this equilibrium, each joint bears the axial force and the joint torque to maintain the geometry of the loaded leg. For a geometry where both joints contribute to leg shortening by a similar amount of rotation the stiffness of the joint springs must be equal to the ratio of the adjacent outer leg segments (Seyfarth *et al.* 2001). Such a layout of joint stiffness has been identified for human running (Günther & Blickhan 2002), i.e. the human leg is driven in a way to assure an equal contribution of both the knee and the ankle joint.

How does the leg behave once it is loaded? The geometry changes during compression. If the joint springs were to develop torques linearly with respect to angular displacement, their contribution to the axial leg spring would be nonlinear, i.e. leg stiffness would change with deflection owing to changes in the lever arm with respect to the leg axis. In the case of an asymmetric design, this change is different for the two joints shifting the compression from one joint to the other. But, even for the symmetric condition after a certain compression, there exist geometries with different leg-compliances for the same leg length. The more compliant mode is a configuration where both the joints are positioned at the same side of the leg axis (bow-mode) in contrast to the stiffer starting configuration with joints on opposite sides of the leg axis (z-mode). Less energy is needed to bend a leg in the bow bode.

Loaded legs run into the danger of hitting a bifurcation and become structurally unstable (figure 4), but different measures can be taken to avoid such a catastrophic event. One is to introduce a short foot segment not aligned with the leg axis. Owing to the angled foot segment rotation concentrates in the ankle and, owing to its larger compliance, it does not force the knee to extend for a large range of displacements (figure 4). The demand of structural stability enforces a human leg configuration. It should also be mentioned that other measures to enhance structural stability consist in the introduction of J-shaped nonlinear stiffness in the revolute springs which counteract the influence of leg geometry or in springs crossing two joints. Biarticular muscles are common (see below). The joint stiffness observed during running is indeed J-shaped with exponents close to the values for proper compensation for geometric nonlinearity, i.e. providing a global leg behaviour close to a linear spring.

The danger of structural instability is enhanced when starting with almost straight legs as is typical for large animals. As mentioned above, small animals use a much more crouched position. Segmented elastic legs with strongly crouched initial conditions do not run into the danger of structural instability. This is even more the case for legs loaded in the bow mode. Such a strategy is, for example, used by spiders which extend their legs hydraulically and are therefore not able to adjust their joint stiffness in a proper way. The same mechanism may be essential at touchdown of the human leg where heel, shank and thigh are configured in a bow-mode.

In spite of the different measures to improve stability, straight legs are much more endangered by structural instability and it is much less demanding to manage bent legs. The trade-off between stability and cost so far has not been addressed quantitatively.

(*d*) *Segmentation and gearing*

The three-segment leg allows for gearing, i.e. for different transmission of muscle velocity into velocities at the leg tip. This may be used while changing gaits.

Sticking to our template, leg movement can be composed of an axial and radial component. Muscles can only generate rotations in the joint. In a joint straightened with respect to the leg axis, a muscle contraction generates rotation but hardly affects the leg length. The inverse is true for strongly bent joints. The fore–aft movement of the leg is generated at the hip joint. If the knee joint is straight, knee rotations modulate this movement. Using a double movement frequency, the overlay of both the components results in a typical sawtooth pattern of the foot movement. The axial movement that is essential at the beginning and the end of the stance phase is mainly supplied by the strongly bent ankle joint. During running, both ankle and knee operate in synchrony and contribute to the elastic rebound represented by the leg spring.

It becomes obvious how muscles can steer and make intelligent use of leg segmentation. We already mentioned the crucial role of the M. tibialis anterior to induce the knee bend during walking after touchdown. The push–pull operation of the ankle and the knee joints enables the biarticular M. gastrocnemius (crossing both the knee and the ankle joints) to shorten quickly and do positive work even at slow locomotion speeds. In running, owing to the increasing coupling between the movement of the ankle joint and the knee joint, the contraction velocity of this muscle is small. Similarly, leg retraction based on hip extension is enhanced by knee flexion (and subsequent ankle extension) in running and reduced by knee extension during walking. Assuming a limited rotational speed (e.g. owing to actuator properties) of hip and knee joints, the tangential speed at the foot is reduced by 50% in walking and increased by 50% in running. Again, changing the internal leg kinematics allows keeping the muscle speed similar at largely altered speeds of locomotion (total increase of 300%). The additional freedom gained by the introduction of a second joint allows for shifting gears between and within gaits without altering the general dynamics of the system.

In the construction of humanoids, legs resembling human legs in segmentation are not just a question of general appearance, but are useful with respect to energy, structural stability and for gearing towards different gaits.

4. Self-stability

The exploration of self-stability in the construction of legged robots may reduce the control effort. For the example of a walker and a runner with a spring-like leg retracted during the swing phase, bumpiness can be ignored provided the central programme ensures a roughly suitable leg stiffness and angle of attack. At the muscle level, basic mechanical properties are essential in order to be able to cope with disturbances.

(*a*) *The idea*

Self-stability represents a measure to explore attractive behaviour of a system without directly sensing deviations from a desired state.

The 'intelligence' of a machine—think about artificial intelligence—is normally localized in its brain, i.e. in its processors and controllers. The fact that engineers so far have difficulties in building machines that display elegant and smooth behaviour may simply rest in deficient software or in limited processing power. However, it may also rest in the mechatronic design of the machine. Movements can be generated by prescribing kinematic patterns and enforcing these patterns by strong motors. The other possibility is to explore the mechanical properties of the machine, which is most prominently shown by passive walkers (e.g. Coleman *et al.* 2001). In this case, the intelligence to coordinate walking is embedded in the mechanics of the system. Self-stability is a further and more extended example for this approach.

It is well known that systems with nonlinear coupling can display chaotic and attractive behaviour. In investigations on motor control, the nonlinear coupling is considered to rest in neuronal circuits. Indeed neurons are highly nonlinear elements. However, in addition, the mechanics of biological systems is inherently nonlinear at many levels. In fact, engineers confronted with similar problems tend to linearize their control algorithms. A much more effective strategy reducing energy cost and control effort is to use the effects of nonlinear mechanics, i.e. use the attractive behaviour of the system. The layout of the system should enforce attractive behaviour. Within a neighbourhood, attractive behaviour implies stability, i.e. robustness with respect to disturbances and stochastic deviations. Pure passiveness may be approached in special cases, but in general all animals (and engineers) use at least some control. We do not want to get stuck with a single behaviour or state. Correspondingly, we have to cope with systems that entail active elements (drives, muscles). They allow changes, but they must be controlled. Stability of the state may be enforced by control.

In this case, the variable characterizing the state is monitored by sensors and the respective information is used to correct for deviations from the desired state (feedback). However, it is also possible that active systems are stable without directly measuring the disturbance. The system corrects for this disturbance by exploring local attractivity of the mechanical system. We call this self-stability (Ringrose 1997; Kubow & Full 1999; Jindrich & Full 2002; Blickhan *et al.* 2003).

It may well be that the search for self-stable conditions can help in the construction of walking machines. To make use of this effect, it is necessary to relieve the construction from stiff feedback control and enhance the freedom for nonlinear interaction.

(*b*) *Running across rough ground*

A robot-runner with quasi-elastic legs is able to accommodate rough ground without changing system properties or movement strategies.

The major advantages of walking machines as compared with wheeled vehicles rest in their behavioural variability and their ability to cover rough ground. Especially during fast locomotion, sensory flow with information about the environment becomes high and time to react becomes short. In biological systems, an additional difficulty is introduced by synaptic delay and the chemo-mechanical transduction process which delays force development. However, the bottleneck owing to sensory flow is well known in robotics, and even if reactions can be provided rather fast it must be ensured that they are correct in terms of the movement goal. It is obvious that a mechanical system which has a built-in answer to unexpected disturbances has enormous advantages.

How does a quasi-elastic system respond to disturbances? At first glance, this seems to be rather simple. Compliance is an advantage in itself as it implies a gradual build-up of force. However, when running is considered, the situation becomes more difficult. An elastic runner must adjust the angle of attack of the leg carefully in order to ensure periodic movements for a given mass and leg stiffness. Changes in the angle of attack result in acceleration or deceleration. A runner facing a step in ground level suddenly seems to have a wrong initial condition for periodic movements. In early bouncing machines, stability is achieved by adjusting the leg angle from step to step, i.e. by acceleration and deceleration. Looking more closely to this interdependency we found that there exists a narrow range of angles of attack where the system can cope with the disturbance in a self-stable manner (Seyfarth *et al.* 2002; Ghigliazza *et al.* 2003). The planar system is nonlinear and for a small range of angles of attack it is within the attractive region of a fix point. While we run, we use a leg stiffness which gives us a rather comfortable ride and use an angle of attack which does not force us to any adjustments (figure 5) in the face of minor deviations in the ground level (up to about 10% of leg length). Even more, the mechanism to stabilize the system without actually sensing the disturbance (self-stability) works better the higher the running speed is.

The small range of angles of attack is still demanding for a control system. The way out is to use retraction, i.e. to move the leg backwards relative to the body just before hitting the ground (Seyfarth *et al.* 2003). Owing to this gripping motion, the angle of attack changes depending on flight time and thus the change in ground level. An upward step in the ground results in a flatter angle of attack

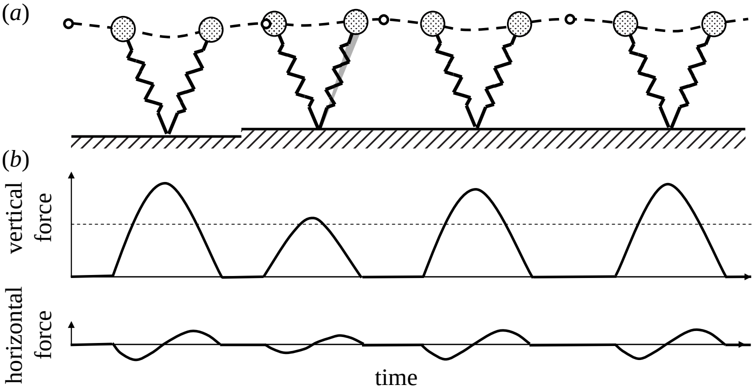

Figure 5. The spring-mass model amortizes a step without altering stiffness or the angle of attack at touchdown. Owing to the step, the flight phase is shortened and the system takes off at a steeper angle, recovering in the next step. The vertical as well as the horizontal components of the ground reaction force are diminished after the step. (*a*) Dashed line, path of the centre of gravity; open circles, apex; shaded sector after second contact: change in take-off angle. (*b*) Dashed line, body weight (after Blickhan *et al.* 2003).

and a downward step in a steeper angle of attack. These are adjustments in the correct direction and thus retraction largely enhances the range of angles in which stability can be achieved. It can be shown that a perfectly tuned leg retraction program could completely compensate perturbations (e.g. ground level changes) within a single step, i.e. the non-perturbed global kinematics is restored after one contact phase.

We have seen that the elastic template is also useful for walking. In walking, parameter combinations were found for which self-stability can be achieved (Geyer 2005). The investigation of the role of retraction to enhance and connect those spaces is underway. With retraction it is possible to run stable at walking speeds. For fast walking, intelligent use of segmentation and timing of the counter-moving legs and joints seems to be crucial. In summary, an elastic leg seems to represent a smart device to cope with rough ground.

(*c*) *Actuator properties*

Actuators with muscle-like properties could display well-tempered behaviour under unexpected load conditions and may facilitate control.

Muscles themselves are frequently treated as springs, but they are much better described by variable dampers. Simulation studies revealed that spring-like properties can be generated via positive force feedback (Geyer *et al.* 2003). Such a positive feedback seems to be a common nature in extensors (Prochazka *et al.* 1997; Cruse *et al.* 1998). Introducing a positive feedback seems to be surprising in the eyes of some engineers as such a circuit should produce catastrophic results. In the case of a runner, it is however necessary to consider the circuit in the context of the mechanics of the system and its building blocks. The dangerous situation of high forces is avoided by limits in activation, by the fact that a muscle reduces force output even though stimulated maximally with increasing shortening velocity and by the take-off of the mechanical system which automatically reduces the load with respect to the environment. The extent to which this feedback may play a role in speed change and gait transition remains to be explored. The usefulness of positive feedback in technical systems depends on the mechanical behaviour of the system and the system components. Whereas unloading during take-off can be enforced with a powerful drive, no successful attempts are available to build drive units (motor and gears) with a muscle-like force–velocity curve and a suitable compliance. The demand for such properties is even more pronounced when the immediate reaction of the system is taken into account.

Owing to the synaptic and electro-mechanical delays, even under feedback control, the immediate reaction of the system is dominated by intrinsic muscle properties. For the biological system that hits the ground unprepared, the immediate reaction within delay time might push the system into a bad and an undesirable state. Simulations of periodic motion show that the muscle itself is well suited to cope with this situation (see also van Soest & Bobbert 1993; Loeb 1995; Wagner & Blickhan 1999). When the muscle yields, it enhances the force owing to the negative slope of the force–velocity curve. This friction, which is actually a result of the molecular mechanism of force production, is crucial for the stabilizing effect of the skeletal muscle. It is further enhanced for the case that the muscle operates at the positive slope of the force length curve in which force increases for the same stimulation rate owing to the increasing overlap of the molecular force generators.

Moreover, self-stability sheds new light on complicated geometrical arrangements like our knee joint with a moving axis of rotation (Wagner & Blickhan 2003). This moving axis of rotation partly compensates for the strong and nasty dependency of the effective mechanical advantage on leg length in the almost extended position and therefore supports the stabilization of the joint movement. Another mechanism to increase the stabilizing effect is to co-activate antagonists, a situation all of us can observe once we learn a new movement. In this case, the necessity of stabilization is energetically demanding and rather tiring. We can take the criterion of stability to predict the activity of the antagonistic muscle. The advantage during learning must still be substantiated experimentally. A neural network (Maier *et al.* 2000) which learns to drive a simple musculoskeletal model for running needs only half the trials if the leg has self-stabilizing properties (H. Wagner 2005, personal communication). This seems to be a huge advantage providing sufficient evolutionary pressure.

So far in artificial muscles, research only focused on compliance. Our research demonstrates that its inherent active damping properties seem to be equally important. The advantage of a muscle-damping property is that it requires an active state and is switched off in the inactive state. A joint with a muscle-like drive can passively swing with only minor friction. This saves energy. As soon as the leg takes up a load it has an inherent damper to sudden disturbances. In fact, here again the system is not just damped. As in the case of the attractive spring-mass system, disturbances are compensated without altering the activation of the muscle.

Recent experiments with simple robot legs (see below) accentuate the usefulness of the asymmetric muscle response with increased force during lengthening owing to friction. Standard springs behave symmetrically with respect to the loading direction. The biarticular muscles in the thigh support knee extension during retraction (M. rectus femoris) and knee flexion during

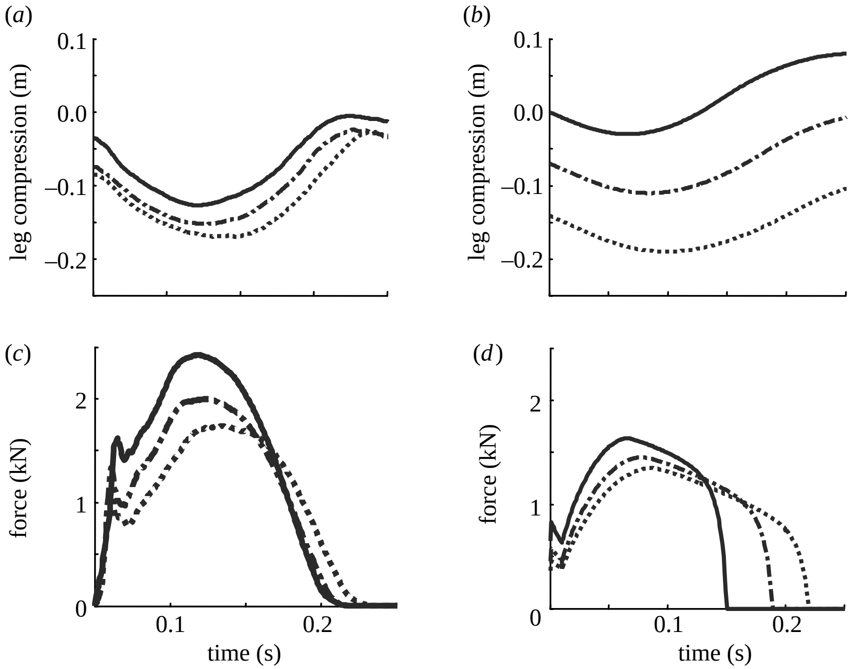

Figure 6. Leg compression $(a,\ b)$ and ground reaction force $(c,\ d)$ while running up steps of different height (0 m, solid line; 0.1 m, dashed line; 0.15 m, dotted line) embedded into a rough ground. $(a,\ c)$ Experiments; $(b,\ d)$ simulation with a two-segment extensor model without elasticity. The experiment $(a,\ c)$ reveals that initial condition is changing with respect to initial velocity (step height), adapted leg length and initial angle of attack of the leg. Compression during contact remains the same, whereas force reduces with step size. Correspondingly, leg stiffness is decreasing. The simple model runner does not match all figures but displays similar tendencies under roughly corresponding initial conditions (initial leg lengths in sequence of the step height: 0.95, 0.9, 0.85 m; angle of attack: 71, 67 and 63°; mass = 60 kg; vertical touchdown velocity $= -0.7\ \mathrm{m\ s^{-1}}$; horizontal touchdown velocity $= 4.5\ \mathrm{m\ s^{-1}}$).

protraction (M. biceps femoris). In both situations, the corresponding muscles lengthen and provide sufficient force against the propelling antagonist. The asymmetric property seems to be an essential feature in the generation of an automated and eventually self-stabilizing stepping cycle. The muscle with its unique properties is an essential building block for self-stability of the locomotor system.

(*d*) *Experimental evidence*

Self-stability theory is supported by experimental evidence.

The legs of human runners use stiffness and angles of attack at touchdown which closely matches the predictions for self-stable movements. First, preliminary data on human running across rough ground are currently evaluated (figure 6). In a situation in which the runner was well aware of the steps of different height, force was reduced following the predictions. Leg length at touchdown is shortened proportional to the height of the obstacle and leg compression remained constant. Thus, stiffness is reduced in proportion.

The criterion of self-stability predicts the selected combinations of stiffness and angle of attack (Seyfarth *et al.* 2002). A shorter leg length at touchdown implies increased bending in the joints which in turn results in decreased effective mechanical advantage. For the same muscle activation, this results in an automatic decrease in leg stiffness. It is possible that the stiffness adjustment is automatic. The adjustment in leg length, i.e. in geometry could be in principle generated without sensing the ground level by the gripping motion. Whether this scenario is sufficient to explain the observed patterns is under investigation. The dominating result of the extensive literature about running on surfaces with different visco-elastic properties is that stiffness of the effective leg including the ground is maintained (Ferris & Farley 1997; Ferris *et al.* 1998).

5. Dealing with the impact at touchdown

Muscle-like drives could serve as an adaptable shock-absorbing unit.

As indicated above, a compliant leg facilitates solving the contact problem but it does not solve it completely. Any real system must cope with distal masses. During locomotion, either the velocity of the foot with respect to the ground is carefully adjusted reaching zero at contact or the system must face an impact at that very instant. The momentum generated equals the product of the effective mass of the foot (and leg) and its touchdown velocity. The generation of this momentum must be damped efficiently as otherwise the bouncing foot loses its grip. We did already mention that at least for large species, such as human walkers and runners, forces are directed towards the hip or the centre of gravity which implies the generation of horizontal forces. The latter require sufficient ground friction. A bouncing foot cannot provide sufficient foothold. Moreover, the energy of the impact can be rather destructive with respect to the system especially to its joints. As inertia of the segments prevents immediate elastic bending of the leg, the impact shock is transmitted through the whole skeletal structure. In fact, for human runners this impact can still be measured in the scull despite several damping strategies.

Correspondingly, to avoid a large energetic and control effort and to still enhance lifetime of the system as well as to secure foothold, countermeasures are necessary. One countermeasure consists of nonlinear visco-elastic properties of the impact surface (heel pad, foot sole). Besides its shock-absorbing property, this tissue is comparatively stiff with respect to shear forces. To improve or at least not to worsen these properties is the business of many research laboratories in the shoe industry. Another countermeasure consists of minimizing distal segment weight. It is well known that in legs muscle mass is shifted proximally. This can be done within segments, consider for example the proportions of the shank, or it can be done across segments, consider fingers and toes. In addition, geometry can contribute to improved foothold. Rolling around the heel at heel strike redistributes the momentum from the horizontal to the vertical component. This is already explored by the shoe industry. The increased deformation of foot and substrate enhances form fit and traction (Ruina *et al.* 2005). A fourth measure is to give the skeleton and its joints shock-absorbing attributes. This is most obviously realized in the spine. In legs with long bones, compliance and viscous damping is concentrated in the joint area. The introduction of large gliding surfaces, covered with visco-elastic cartilage, has

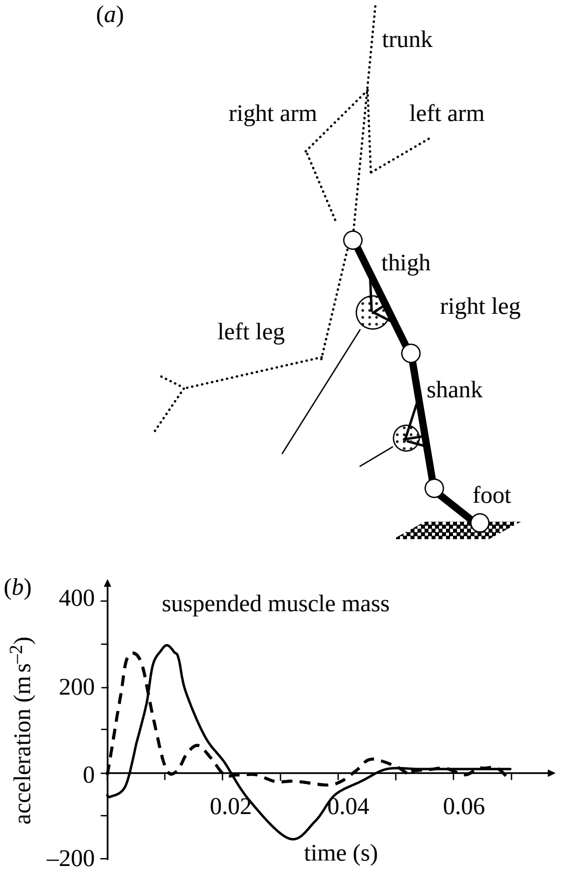

Figure 7. (*a*) Visco-elastically suspended muscle masses at thigh and shank. (*b*) Line: acceleration measured at the surface of the shank, note the delayed damped oscillation; dashed line: acceleration of the tibia relying on surface marker kinematics at the ankle joint (after Günther *et al.* 2003).

a distinct advantage as compared with stiff steel axes and ball bearings. Last but not the least nature employs another trick to reduce the detrimental effect of the impact. It consists of suspending drives visco-elastically to the skeleton (figure 7; Günther *et al.* 2003) and works like the shock-absorbing systems in skyscrapers. Besides the bones, the major masses of the leg consist of muscles, the natural drive. This sheds a new light on the meaning of muscle compliance. But being compliant would not be of much help as ringing of significant suspended masses would be rather annoying. Moreover, control would be hampered. At this point again, the viscous properties of the activated muscle come into play. Walking and running on a hard surface demand costly increased muscle activation to suppress ringing (Wakeling & Nigg 2001). The muscle tissue recruited with increasing speed not only increases force, but also damps the increasing impacts. Viscous damping of an activated muscle as described in the force–velocity curve results in a close to critical damping of ringing muscle masses. A considerable fraction of the impact energy is absorbed by this shock-consuming system. Again, the combination of compliance and active viscous damping within the muscle must be tuned to achieve this goal.

6. Perspectives

Our research on biological objects revealed insight into some principles of construction and control which are relevant in the field of legged machines.

Construction.

- (i) Speed-dependent adjustment of leg compliance allows for dynamically correct and smooth walking and running including the difficult gait transition.
- (ii) Joint stiffness must be adjusted to the segmentation to ascertain shared contributions to leg compliance.
- (iii) Human-like segment lengths and orientations save energy and support structural stability.
- (iv) Where matched joint properties cannot be achieved, the more expensive and compliant bow-shaped configuration is more suitable.
- (v) Owing to dramatic changes in mechanical advantage, changes in local gearing such as moving axes of rotation help to maintain stable loading.
- (vi) Drives with a certain inherent compliance and a negative slope of the force–velocity characteristic provide immediate and stable response in the face of disturbances and may help automatize the stepping cycle.
- (vii) The detrimental influence of the impact can be largely reduced by visco-elastic suspension of the massive drive.

Control.

- (i) Positive force-feedback may be used to provide stable cyclic bouncing behaviour of joints and legs.
- (ii) The compliant leg might be used as a central template to facilitate control of dynamic movements and to be able to adjust locomotion speed.
- (iii) Self-stability should be explored to reduce demands on control and avoid the bottleneck of sensory flow.
- (iv) With well-chosen leg properties, a suitable angle of attack at touchdown allows self-stable walking and running.
- (v) Retraction of the swing leg does support self-stability.
- (vi) Correct orientation of the leg segments at touchdown enhances structural stability.
- (vii) Differential use of leg segments especially by proper activation of biarticular drives provides geared use of the leg during walking and running.
- (viii) Co-activation of muscle-like antagonists enhances stability.
- (ix) The shock-absorbing capacity of muscle-like drives can be adjusted by activation.

For engineers facing a major difficulty to find lightweight drives sufficiently strong to generate the torques for dynamic locomotion, elastic and self-stable legs seem to be of secondary interest. On the other hand, it seems that if such basic properties are not envisioned at the start of the design process, their

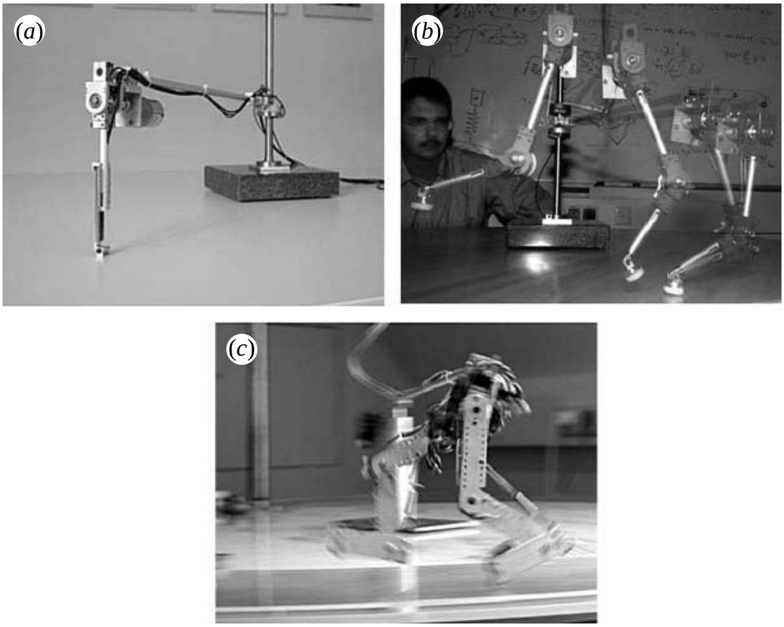

Figure 8. Examples of elastic legged robots (Locomotion Laboratory Jena). In all cases, locomotion was found without sensory feedback by merely introducing oscillatory fore–aft movements at the hip. (*a*) Pogo stick runner; (*b*) two-segment runner; (*c*) biped with elastic three-segment legs. Based on the mono- and biarticular elastic coupling, stable walking with human-like knee and ankle joint kinematics (similar to figure 2*b*) is found.

implementation later on may become at least difficult or even impossible. The main advantages of the design criteria elucidated above are reduced control and energetic effort as well as enhanced lifetime of the product.

Compliance of the leg can be realized by passive elasticity. This has been tested in the first hopping machines and many bouncing successors. Recent experiments in the Locomotion Lab at the University of Jena are promising with respect to passively compliant walking and running (figure 8; Iida 2005). They have largely contributed to our understanding of compliant leg operation in walking and running, the role of axial and rotational components, the intelligent use of joints, and the role of biarticular muscles therein and the role of hip compliance to cope with impacts. These experiments give further insight with respect to the consequences in the layout of stiffness and segmentation. Most important, they have demonstrated that simple, slightly forced oscillatory movements in the hip joint can be successfully used to generate both walking and running.

Another possibility would be to introduce compliance using control. This might be suitable in a test phase as its implementation seems to be straightforward and may represent a rather flexible solution. As all enforced solutions, it may turn out to be energetically expensive. Moreover, possibilities may turn out to be rather limited. Motors facing friction and inertia of large gearing boxes may not be able to produce compliant behaviour. It is very likely that a decent passive response at the instant of touchdown is almost indispensable. It would give the system time to adjust to the prevailing conditions. In this respect, it seems to be important that the system provides not only compliance but also suitable damping. Undamped compliant systems are prone to ringing and hard to control. The introduction of dampers, however, increases the cost. The solution in the animal kingdom of using a compliant drive with activation-dependent damping may be an ideal solution and the search for such a drive seems to be an important general research goal. Once the drive embodies compliance and viscosity, and once it can be controlled, it may turn out not to be difficult to suspend it visco-elastically and to use it as an element within a general shock-absorbing system.

Self-stability facilitates control. As it depends on the global system properties as well as the layout of all major building blocks, it is helpful to check whether selected designs can provide self-stability or the motion goal must be enforced against chaotic behaviour of the mechatronic system. So far, only small and simple systems (e.g. Rhex; Saranli *et al.* 2001) explore such properties. Here, we find an excellent field to apply dynamical simulation in advance. Moreover, only the tip of an iceberg has been scratched in this research and a much deeper understanding of the complex interactions seems to be necessary. Nevertheless, the outlook is quite promising. Running is impossible without at least mimicking compliant legs. By using correct movement strategies, self-stability can be easily implemented.

In the context of rehabilitation, the deeper understanding of basic operation of the locomotor system helps to improve the design of prostheses and of exercise protocols. Design of prostheses and robot legs are mutually stimulating. For us, corresponding applications represent experiments which may support or falsify our ideas about the organization and function of living motion systems.

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