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Concepts of Softness for Legged Locomotion and their Assessment

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Abstract In human and animal locomotion, compliant structures play an essential role in the body and actuator design. Recently, researchers have started to exploit these compliant mechanisms in robotic systems with the goal to achieve the yet superior motions and performances of the biological counterpart. For instance, compliant actuators such as series elastic actuators (SEA) can help to improve the energy efficiency and the required peak power in powered prostheses and exoskeletons. However, muscle function is also associated with damping-like characteristics complementing the elastic function of the tendons operating in series to the muscle fibers. Carefully designed conceptual as well as detailed motion dynamics models are key to understanding the purposes of softness, i.e. elasticity and damping, in human and animal locomotion and to transfer these insights to the design and control of novel legged robots. Results for the design of compliant legged systems based on a series of conceptual biomechanical models are summarized. We discuss how these models compare to experimental observations of human locomotion and how these models could be used to guide the design of legged robots and also how to systematically evaluate and compare natural and robotic legged motions.

Biomechanics of Legged Locomotion

Computer simulation models can be very powerful tools for analyzing and describing human and animal locomotion. In the last years sophisticated human motion simulation environments have become widely accessible to the research community both for forward dynamics (e.g. OpenSim [5]) as well as for inverse dynamic calculations (e.g. AnyBody [4]). These software tools can be used to describe human (or animal) motion dynamics as the result of the interaction between body mechanics and actuator (muscle) dynamics. However, because of the very large number of parameters and submodels involved their validation and calibration is highly challenging and not yet reasonably solved. In contrast to these detailed models there is an increasing number of conceptual models which are designed to understand the basic mechanisms of legged locomotion. These models are mostly based on the inverted pendulum model (IP) [1] or on the spring-loaded inverted pendulum model (SLIP, originally introduced by Blickhan [2] and McMahon and Cheng [22]). Both models can be considered as template models [11] as they describe the key mechanics of the center of mass (CoM) during legged locomotion at a most reduced level of detail.

In the IP (inverted pendulum) model, the distance between the CoM and the contact point at the ground during stance phase is assumed to be constant. Hence, the CoM is travelling on a circular arc over this support point at the ground. In contrast, in the SLIP (spring-loaded inverted pendulum) model — a two-dimensional spring-mass model — the leg operates similar to a linear prismatic spring. Here, the distance of the CoM to the support point is not constant. For instance, in running the leg first compresses and finally decompresses until the end of contact. The characteristic loading-unloading cycle of the conceptual leg spring is associated with a typical sinusoidal pattern of the ground reaction force (GRF). This basic leg mechanics can also be found in other bouncy gaits such as human hopping [10] and jumping [29] or quadrupedal trotting [15].

An analysis of experimental data of human running reveals that the leg indeed compresses with leg force being about proportional to the amount of leg shortening [20]. This experimental observation has led to the concept of a leg spring. Here the leg spring constant, called *leg stiffness,* describes the ratio between the maximum leg force and maximum leg compression (the amount of shortening of leg length during contact). It is important to note that this ratio only describes an overall spring-like leg *behavior* represented in the force-length relationship and does not necessarily reflect the action of a single mechanical (passive) or controlled (active) spring. For example, also a mass which is moved up- and downward by being attached to circulating disc will generate a spring-like behavior, meaning that the force generated in a harmonic manner will lead to a 180° out-of-phase relation between force and position of the mass. Hence, the concept of the leg spring is less representing a real spring but rather the mechanics of a harmonic oscillation, which may be the result of quite different complex mechanisms (e.g. kinematic program, compliant structures, muscle-tendon-skeleton dynamics).

In case of the human locomotor function, leg forces are generated through muscle activation. The muscle forces are transferred to the joints (as joint torques) through tendons, which operate in series to the muscle fibers. Hence, compliant leg function is determined by the highly elastic properties of the tendons of which many span multiple leg joints. For instance, in the human Gastrocnemius muscle – the large calf muscle spanning knee and ankle – the muscle fiber length is only about 10% of the total length of the muscle-tendon complex [18]. Thus, at higher forces and resulting loading dynamics, the muscle fibers can only partially contribute to overall muscle-tendon work. As a result, the force-length profile generated by the muscle-tendon system is largely determined by the function of the elastic tendon [30]. This elastically shaped muscle function in bouncing gaits (e.g. running, jumping, hopping) translates into the joint function and finally into a leg function, which force-length relationship is very similar to that of a linear spring. The resulting slope of this relationship is often compared to (and sometimes even interpreted as) the "leg stiffness". This comparison (and phrasing) has to be made very carefully, as the observed "leg stiffness" is a combination of both elastic and nonelastic mechanisms, which need to be separated from each other.

In Table 1, selected body and leg spring parameters in human and animal locomotion are summarized providing key reference data for legged robots to achieve comparable motion performance. Please note that the stiffness values provided by Herr et al. [16] are derived based on a computer simulation model to match experimental gait patterns. The leg stiffness values estimated by Lipfert et al. [20] take shifts in the center of pressure (CoP) position during contact into account. Farley et al. [8] found that across different animals, leg stiffness scales to body mass according to $k_{LEG} = 0.715m^{0.67}$. In most of the analyzed animals in this study, leg stiffness was found to be largely independent of speed.

Legged Locomotion in Robotics

Since the beginning of robotics more than 50 years ago, robots for practical applications are predominantly designed by the principle of kinematic chains of rigid joints and links [28]. Mechanical elasticity has been considered harmful. Limited positioning accuracy caused by link deflection due to compliance, which cannot be avoided by robot design, are usually handled by augmenting position control algorithms with models of link deflection in order to compensate for them. The rigid kinematic chain paradigm facilitates a corresponding modular robot design from largely independent building blocks (i.e. joint level actuation, sensing and control). Robot tasks are usually formulated in operational space (e.g., as trajectories of the end effector in world coordinates). In practice, operational space control is commonly approximated by coordinated decentralized, single-input-single-output joint space controllers [3]. Such an approach is feasible for conventional robot designs with relatively high stiffness and low compliance. Elastic and compliant behavior of a rigid robot in a contact task can be achieved by advanced control methods, e.g., impedance control [34].

These concepts for the design and control of powerful robotic arms provided the models for the currently most common four-legged and bipedal robot designs [17]. The Zero-Moment-Point (ZMP) is the best known and commonly used scheme to implement stable bipedal walking for such robots. Virtual compliance, e.g. based on impedance control, and improved actuators provides some of the locomotion performance of humans like jogging type motion with small flight phases of both feet. This approach cannot recover much energy between steps and is therefore highly energy inefficient. It also requires full feedback and sufficiently low latency of the control loop.

Table 1: Selected spring-leg parameters for four-legged animals and humans.

species	mass (kg)	leg length (m)	stiffness fore-limb (kN/m)	stiffness hind-limb (kN/m)	speed (m/s)	gait	Reference
human	73.4	0.97	—	12	2.5	run	Farley and Gonzalez, 1996
human	70.9	0.95	—	23.5	1.55	walk	Lipfert et al., 2012
human	70.9	0.98	—	16.5	2.59	run	Lipfert et al., 2012
dog 1	5.1	0.20	1.9	1.2	1.9	trot	Herr et al. 2002
dog 2	23.9	0.50	2.9	1.9	2.9	trot	Herr et al. 2002
goat	25.2	0.48	4.9	2.7	2.8	trot	Herr et al. 2002
horse 1	134	0.75	18	9.1	2.7	trot	Herr et al. 2002
horse 2	676	1.5	37	22	2.9	trot	Herr et al. 2002

The locomotor system of humans and animals is following another design approach. The biological system would not be capable to realize these state-of-the-art control concepts used in engineering. Its motor system is highly redundant and compliant with many actuators (muscles) spanning one or multiple leg joints and many (individually controlled) motor units with different actuator properties sharing the work within one muscle. At the same time biological signal processing and actuator dynamics are slow. The resulting latencies in the control loop only enable feedforward control of fast motions. Compliant structures (e.g. tendons, ligament, titin) are largely shaping the forces acting on the body.

With increasing motion speed the contribution of sensory feedback to motor control reduces and the system and actuator dynamics are becoming key players for motion generation. Sophisticated control approaches such as ZMP or hybrid zero dynamics (HZD) [33] could not operate on the biological system.

Recently the development of novel variable impedance actuators has gained strong momentum in robotics [37]. These provide promising abilities for compliant robot design including capabilities to store energy and to passively support push off for the next step and to instantaneously compensate for shocks from collisions of the feet with the ground. However, new design and control concepts need to be investigated to fully utilize the potential of these new compliant actuators for legged robots [38] including systematic assessment of actuation and control with muscle-tendon units spanning multiple joints versus compliant single joint actuation only.

With the help of biomechanical template models [11], key parameters of biological motion patterns can be identified and matching control approaches can be derived. For the transfer into technical systems, the key challenge remains to define to what extent the biomechanical template can and must to be represented by the design of the mechanical system and the actuators and what is the contribution of control to shape the body dynamics and motion performance during selected motion tasks.

Biomechanical Concepts for Legged Locomotion

The design process of technical legged systems like legged robots or leg prostheses which mimic the design and function of the biological counterpart can be strongly supported by biomechanical concepts. However, often these concepts are focusing only on specific features of legged locomotion. In order to be useful for the design of technical legged systems, several of these conceptual models consequently need to be extended and combined properly to reach a sufficient level of detail and complexity. In the following we will address how specific design features of the biological system can be combined in a more comprehensive conceptual approach for the design of legged robotic systems.

As pointed out in the introduction, human leg function is largely shaped by elastic properties of muscles and other soft tissues of the human body. Though the tendon properties in the human leg are well defined, the resulting leg function is largely dependent on the leg geometry (e.g. whether the joints are extended or flexed) and on the muscle-tendon dynamics and their interactions during a specific movement. For example, in human standing calf muscles can operate (lengthen and shorten) out-of-phase to the Achilles tendon [36]. For instance, with increasing muscle force, the tendon lengthens while the muscle fibers shorten. As a result, the overall muscle-tendon system acts stiffer compared to the tendon stiffness. In order to separate the effects of muscle-tendon dynamics and leg geometry (leg segmentation and joint angles) in adjusting the overall leg function stiffness (e.g. leg stiffness), models with different levels of complexity have been developed.

In a study of Geyer et al. [12] the architecture of the human leg was reduced to a two-segment model with an extensor muscle describing the repulsive leg function during bouncing tasks (e.g. hopping). In this model it was shown, that based on the characteristic properties of muscle fibers (Hill-type muscle model), a corresponding muscle activation pattern is required to generate cyclic vertical jumps. These patterns can be provided as a feedforward command [13] or as a combination of a constant activation and a modulating feedback signal based on proprioceptive sensory signals. As an outcome of this simulation study, a positive feedback of muscle force was predicted to be best suited in order to achieve stable hopping cycles. Hopping frequency and hopping height could be adjusted based on the feedback parameters (gains, delays). Even though tendon elasticity largely improves hopping height, stable hopping was also possible without any tendons in series to the muscle fibers.

In recent studies of Häufle et al. [13, 14], this model was further reduced to a one-dimensional muscle model operating as a virtual "leg muscle" supporting the body mass. With this model the effects of muscle dynamics were considered independent of leg segment dynamics. The results are in line with the findings of Geyer et al. [12] that muscle function for stable hopping can be achieved by both feedforward and feedback control of the muscle. Interestingly, the combination of both actuation schemes provided the best results regarding energy stability in cyclic hopping.

These two models illustrate that the key mechanisms for achieving repulsive leg function as observed in human locomotion do not rely on elastic elements. The muscle dynamics can be exploited by feedforward and feedback activation schemes to result in the observed spring-like leg operation. Hence, leg compliance is an option (which provides many benefits, e.g. for energetics, stability, and shock resistance) but not required to achieve stable hopping and gaits.

Radial and Tangential Leg Function

The sagittal-plane leg function in human locomotion can be divided into two directions: the radial leg function (e.g., the function represented by the leg spring) and the tangential leg function. The latter includes force contributions, which are directed outside the leg axis. For instance, tangential leg forces can be used to redirect the leg force from the CoM in order to stabilize body posture. In contrast to the radial leg function which is the focus of the IP and SLIP model, tangential leg function has received more attention only recently.

Radial leg function is required to direct the forces outside the leg axis. This is important when you want to kick the ball with your foot. In legged locomotion radial leg function is required in order to adjust the leg angle during swing phase [6] in order to prepare for the next ground contact (e.g. foot placement). At the same time, radial leg function is needed to achieve postural stability (balance) during standing, walking, and other gaits. In human walking, leg forces during stance phase point – in contrast to the bipedal SLIP model – to a point above the CoM. The intersection point is also called virtual pivot point (VPP) [21], as it mimics the function of a virtual support point of a physical pendulum. The extension of the SLIP model by a rigid trunk shows that postural stability in walking and running can be achieved when the leg forces are deviated to a fixed VPP point at the supported body. By shifting the horizontal location of the VPP relative to the body axis (line through CoM and hip), the resulting hip torques will accelerate or decelerate the gait. Interestingly, the hip torques predicted by the VPP model are very similar to those observed in human walking.

The radial leg function is not only a key to redirect leg forces during ground contact (as described by the VPP concept) but may also align the leg angle during swing. A simple model to describe the swing-leg dynamics in locomotion could be a spring-loaded pendulum, which is supported by the upper body (pelvis). Recently Song et al. [32] found that this model is well able to represent the experimental hip joint forces caused by the swing leg during human walking, if swing leg stiffness is adjusted to walking speed. The pendulum length may, however, not only result from the distance of the swing leg CoM to the hip joint but also well tuned by two-joint thigh muscles which can tune the rotational stiffness of the swing leg. Both the rotational swing-mass system and the pendulum are sharing similar dynamics for moderate angular displacements. Hence, the rotational elastic oscillator can mimic and thus tune the virtual pendulum length of the swing leg. With that both balance and swing-leg function could be represented by a similar template model, a virtual pendulum. In contrast to the VPP concept, this pendulum shares spring-like leg properties (as in the SLIP model) also in the radial leg function. Thus swing-leg function can be considered as a superposition of repulsive leg function (virtual leg spring) and balance (virtual pendulum), leading to a spring loaded pendulum model (SLP). These three fundamental subfunctions for legged locomotion (balance, repulsive leg function, and swing-leg function) and the corresponding template models (VPP, SLIP, SLP) are summarized in Fig. 2.

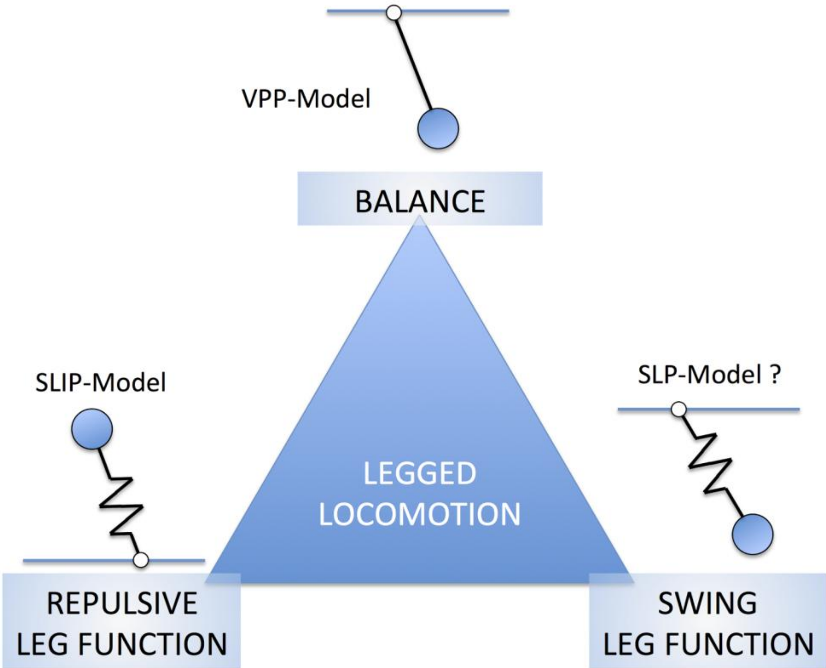

Figure 2: Legged locomotion can be considered as a combination of three elementary subfunctions: balance, repulsive leg function, and swing leg function. For each of these subfunctions, mechanical template models can be identified which describe the dynamics of the center of mass (SLIP model), of the body orientation (VPP model), and of the swing-leg center of mass. The template model for the swing leg function is a topic of current research and could be a spring-loaded pendulum (SLP), as suggested by recent findings of Song et al. 2014 [32].

Leg Segmentation and Multi-Joint Structures

Conceptual models based on the SLIP template show that both the radial and the tangential leg function are complementing each other in order to generate stable gaits and to maintain postural stability during locomotion. However, in the segmented leg, individual joint torques at hip, knee, and ankle will influence both leg functions. How could the biological body take advantage of the matching properties of the both underlying leg functions?

In order to resolve this issue, it would be extremely helpful if the tangential leg function could be accessed independently from the radial leg function. One possible solution is taking advantage of the two-joint (biarticular) structure of some of the leg muscles. These muscles are able to provide specific combinations of joint torques and to exchange energy between leg joints. It turns out that with a proper lever arm design (e.g. hip to knee lever arm ratio of 1:2) these two-joint muscles can generate force contributions, which are perpendicular to the leg axis [27]. Hence, by activating these muscles, leg force contributions will be created which merely contribute to the tangential leg function but not to the radial leg function. With an arrangement of a pair of antagonistic two-joint thigh muscles (like rectus femoris and hamstrings), it is possible to implement the VPP concept independent of the function of the single-joint muscles (which could contribute to the radial leg function). Hence, the architecture (geometrical arrangement) of leg muscles could be a key in providing differential access to the tangential leg function as a complementation of the radial leg function.

Currently, these ideas and concepts are substantiated by taking compliant properties of two-joint muscles into account. This research may lead to insights how radial and tangential leg functions might be adapted to each other and to what extent the control of body posture can be solved in a generalized way that includes a free selection of a large variety of motion tasks ranging from standing, walking, and running gaits.

From Biomechanical Concepts to Robots

In the BioBiped project (www.biobiped.de) the focus is on exploring the roles of the musculoskeletal actuator arrangement in a humanoid robot with segmented legs. The two built prototypes BioBiped1 and BioBiped2 feature three-segmented legs with nine active and passive, human-like muscle-tendon units per leg spanning one or two joints [39]. Based on the human lower limb system, the hip, knee, and ankle joints are spanned by a pair of monoarticular antagonist-agonist, series elastically actuated (SEA) or passive tendons, as shown in Fig. 3(c). The biarticular muscles found in humans are realized as passive tendons with built-in extension springs connecting two segments.

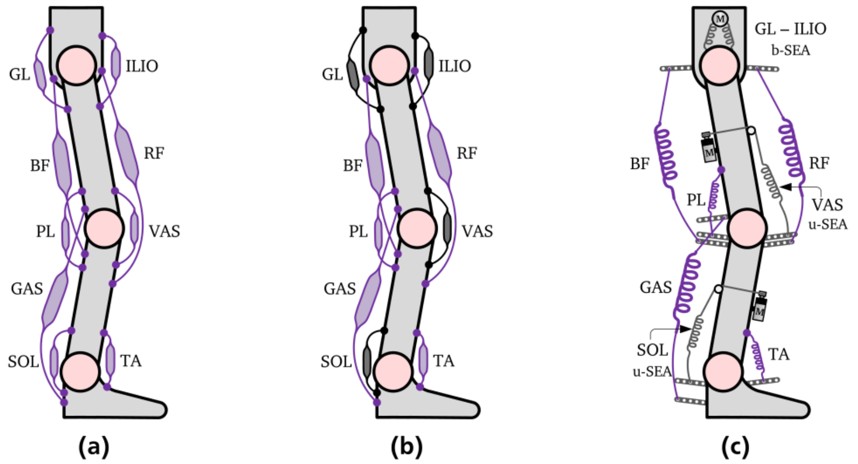

Figure 3: Evolution of BioBiped1's actuation concept: (a) human musculoskeletal leg system; (b) selection of actuators and passive elements: the hip joint requires both active flexion and extension, while in the knee and ankle joints only actuated extensor muscles are required (highlighted); c) implementation of passive and active elements as motors and springs [23].

With this novel, specifically selected musculoskeletal design a number of research questions can be addressed. This hardware-based research approach is complemented by a sufficiently realistic modeling and simulation methodology [19,23,24]. Passive rebound studies in simulation investigating different actuation designs demonstrated that dynamic and energy-efficient locomotion cannot be achieved through stiff actuation without causing critical damage to the motor gearboxes [26]. More importantly, it was shown that the energy restitution ratio increases with joint compliance. However, exceeding a specific leg compliance will negatively affect the energy restitution and also the dynamic performance, e.g., for hopping the hopping height and duty factor. Thus, applying a kind of "cascaded optimization" to optimize, first, the actuation with respect to energy restitution and other selected performance criteria such as hopping height and ground clearance and, subsequently, to optimize the controller gains to keep the torques of the motors as low as possible is an essential requirement for an optimal use of the leg actuation design [23]. Open-loop controlled motions revealed that omitting a careful selection of all regulating parameters of the design space, i.e., rest lengths, attachment points, spring stiffnesses, may lead to timing issues of the tendons interfering with each other. The simulation results also showed that actuated biarticular tendons can further reduce the complexity of the leg actuation design and enhance energy savings, while preserving the desired dynamic locomotion behavior.

Demonstrating the importance, an earlier insight from biomechanics, known as the Lombard paradox, was rediscovered and explored using detailed multibody system dynamics simulations [25]. According to the Lombard paradox, biarticular muscles have even more sophisticated functionalities than usually assumed. They are responsible for additional actions during dynamic locomotion. For example, the Gastrocnemius muscle is not only responsible for flexing the knee joint. During the last part of ground contact phase during sprinting, it also acts as synergist extending the knee joint at angles above a specific flexion degree [35]. Such muscle action, labeled by Lombard in 1903 the "paradoxical" function of biarticular muscles, was also observed to be true for the hamstrings. Applying this paradox, a novel bipedal locomotion model could be established that is capable of dynamic hopping motions without the need of a knee motor, leading to energy savings of more than 60 %. In an earlier work it was suggested that an active knee is not required for level-ground walking [7].

In summary, these findings are encouraging for advancing musculoskeletal robot designs with enhanced locomotion capabilities. By subsequently refining the robot's design and control, biomechanical concepts can be demonstrated, validated technical legged systems and new insights (e.g. hidden paradoxical findings) can be revealed.

Assessment of Locomotor Function in Biomechanics and Robotics

The development of proper conceptual models for human locomotion is key in separating underlying task-specific subfunctions required to achieve stable gaits. For legged locomotion, three functional requirements need to be fulfilled [31], as shown in Table 2.

Table 2: Functional requirements for legged locomotion.

	Repulsive leg function	**Body balance**	**Leg swing**
Purpose	Counteract gravity by rebounding body vertically during stance	Counteract gravity by aligning body axis vertically	Position swing leg for next touch-down
Underlying template	Virtual inverted elastic pendulum (SLIP)	Virtual pendulum (P)	Virtual elastic pendulum (SLP)
Key properties	Leg stiffness, leg length, leg angle	Virtual center of rotation (VPP position)	Pendulum length, leg stiffness
Parameters for assessment	External work on CoM, leg length, energy, power, elastic capacity, leg lengthening	Internal work on body pitch, body angular momentum, pitch excursions	Internal work on leg swing, leg swing amplitude, swing leg shortening

These subfunctions required for legged locomotion can be used as a basis for a more functional description of locomotor function in humans, animals, and robotic systems. This is extremely helpful as the design and the ways of actuation as well as the materials of these systems may be quite different. With this matrix of functional requirements the identification of deficits in current legged robotic systems in comparison with their biological counterparts could be largely facilitated. It remains for further research to identify which of these elements are most important for comparison of different locomotor systems. Also, the list of the task-specific subfunctions might be incomplete which would require an extension of the conceptual models.

Aside from this biomechanical approach, it is crucial to develop and apply measures to rate key criteria of locomotion performance across different models, i.e., simulation models of motion dynamics of humans or robots. This goal can be achieved within two steps and represents a milestone for developing generally applicable benchmarks to foster the progress in the robotics community.

The first task is to specify essential aspects of human locomotion to be transferred to robot systems by mathematical models. These aspects are expected to be partially complementary and competitive criteria to each other (such as locomotion speed and energy consumption). A comprehensive catalog of locomotion performance criteria for various gaits should include preferably dimensionless criteria from relevant categories: (1) energy-efficiency (e.g., mechanical and electrical energy consumption, energy restitution ratio [23], kinetic and potential energy fluctuations), (2) dynamic mobility [23] (e.g., altitude difference of the center of mass (CoM), duty factor, speed), (3) control efforts (i.e., proportion of feedback versus feedforward control influence, sensory information resolution and processing speed), (4) postural stability and (5) robustness against disturbances.

It is hypothesized that by validating the three above suggested biomechanically motivated functional requirements for legged locomotion (Table 2) as well as the application of an aggregation of mathematical models of the aforementioned categories will help to better understand biomechanics of locomotion and to use these insights to advance the design and motion dynamics of technical legged systems toward human-like locomotion in appearance and performance.

Outlook

Although compliant leg function is an obvious key feature of human and animal locomotion such as walking, running or jumping it is still not sufficiently understood to directly transfer it to legged robots or leg prostheses with similar motion performance. Originally attributed mainly to the axial leg function, it became clear that also non-axial force contributions are shaped by elastic components. The origin of elastic leg function can be found in the design of the muscle-tendon units, in compliant structures (e.g. ligaments) in the human body. It requires an appropriate neural control to result in the required muscle activation patterns for elastic, repulsive operation of the leg. The leg function cannot be simply implemented by compliant structures as they cannot respond to unexpected changes in the environment (e.g. uneven ground, slopes, pushes) or in the body adequately (e.g. changed body mass when carrying weights).

In order to be able to achieve versatile compliant leg function in a variety of tasks and conditions, a careful design of body, actuator and control properties arranged in a segmented body is required. Here, the underlying mechanisms are still largely unclear and require further research, e.g. regarding following aspects:

- What kind of muscle properties needs to be implemented in a technical system (e.g. serial/parallel compliance, damping, activation dynamics) in order to realize comparably efficient and versatile tasks?
- How can complex scenarios of motion and interaction with multiple contacts be realized (e.g. with hands and feet contacts)?
- What is different between leg function and arm function regarding their motor function capabilities?
- How do biomechanical templates relate to biological control concepts? Are there also neuromuscular control templates matching the biomechanical templates?
- Do we need new kind of materials and actuator properties to mimic human-like locomotion in technical systems? What are proper models for human- or animal-like motion performance?

Currently, a new technology of 3D-printed elastic materials is evolving, e.g. for designing custom-made shoe insoles (www.rsprint.be), orthoses (Ekso Bionics) or prostheses. These technologies need be further developed to achieve adjustable compliance also during operation (e.g. in response to changed environments or subject conditions).

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