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Towards Human-Like Bipedal Locomotion with Three-Segmented Elastic Legs

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Abstract

The long-term goal of the recently launched project BioBiped is to develop autonomous bipedal robots that are capable of energy-efficient multimodal locomotion. In this paper we give a brief review of the important insights and techniques gained in previous and current projects leading to a new generation of human-like robots. Furthermore, we present the hardware design and the applied principles for the bipedal robot with three-segmented elastic legs that is currently under development. In the latter part of the paper we describe optimization methods that yield optimal parameter sets for tuning the walking and running gaits for a robot prototype with the same kinematic leg design.

1 Introduction

Versatile and energy-efficient robots are object of interest in many areas, not only in service robotics which comprise domestic and public servicing [1], leading to robots which help humans at home, in hospitals, shops, etc., but also in space robotics which poses high requirements regarding mobility and autonomy and in rescue robotics in dangerous missions where human life would be at risk. Particularly legged robots are beneficial in diverse scenarios, since legs make it possible to move on smooth and rough terrain, to climb stairs, to avoid or step over obstacles, and to move at various speeds.

If compared with biological systems that routinely exhibit dynamic behaviors in complex environments, however, our legged robots still severely lack diversity in locomotion, from slow, feedback-controlled to fast, feedforward-controlled motions. Existing robots are still energetically inefficient and lack performance and adaptivity when confronted with situations that animals cope with on a routine basis.

Bridging the gap between artificial and natural systems requires not only better sensorimotor and learning capabilities but also an appropriate motion apparatus with variable elasticity. In general, a prerequisite for developing robots with human-like movements is understanding the fundamental principles underlying legged locomotion. The direct transfer of methods from control engineering to legged robots that have to perform in the real world has not yet resulted in human-like robot locomotion. It is essential to work out principles of biological systems and transfer these to robot design, thus achieving mechanical intelligence [2]. For it should be clear that even the best software can not overcome the limitations of hardware [3]. In total three main challenges can be agreed upon when developing biologically inspired systems with partially passive dynamics [4]:

1. systematical exploration of the basic mechanisms of self-stabilization including additional functional elements such as adjustable spring-damper regulators and basic feedback loops (e.g. reflexes),
2. roles of morphology in underactuated systems with respect to behavioral diversity,
3. using computational optimization tools to tackle with the problem of controlling nonlinear dynamics.

A further key component of versatile and energy-efficient robots that move in a-priori unknown environments are proper actuation modules [5]. It is also important to note that the control of the system can be kept as simple as possible by benefitting from the intrinsic dynamics of the mechanical system.

In this paper we give an overview of the principles and design methodologies that are necessary for the development of human-like bipedal robots by touching on the different existing groups of bipedal robots. In this context, the recently launched project BioBiped is introduced. In the latter part of the paper we describe useful optimization methods for tuning the gait parameter sets for a given robot prototype.

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2 Three Main Categories for Legged Robots to Date

The works in the field of legged robots can be categorized into three groups. The first one comprises **conventionally built robots** such as Asimo or Bruno (see **Fig. 1**). These are robots based on kinematic chains of rigid rotary joints and links [6]. They can reliably perform a variety of stable walking motions. However, their locomotion lacks the compliance and elasticity that can be observed in human's jogging and running gaits. Their design is furthermore based on the principle of fully actuated and fully feedback controlled joints. Such robots cannot exploit natural dynamics and self-stabilization of dynamic human locomotion. This group is currently still dominant and makes particularly use of the zero-moment point (ZMP) criterion [7] and its variations to make sure that the robot does not fall over.

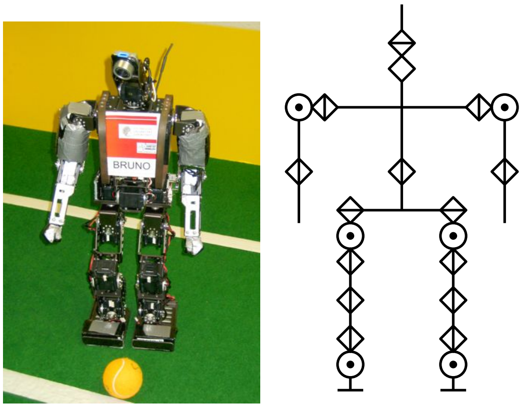

Figure 1: Left: the humanoid robot Bruno (DD2008 model). Right: its kinematic structure.

The second group was launched and is dominated by the computer-controlled walking machines of Raibert [8]. Controllers based on a **spring-loaded inverted pendulum model** are used to achieve stable gaits. Raibert proved that the control of such system could be split into three separate components: the first controls the altitude by providing a fixed thrust during each cycle; the second part controls the forward velocity of the whole system by assigning to the foot, at each step, a given distance from the hip when landing; and the last one controls the body attitude by servoing the hip during the stance phase. Interestingly, this rather simple approach applies almost straightforwardly to the case of the 3D one-legged hopping robot and can be also extended to biped or quadruped robots (see **Fig. 2**). A sequence of active hopping robots with one, two and four legs were designed with impressive results.

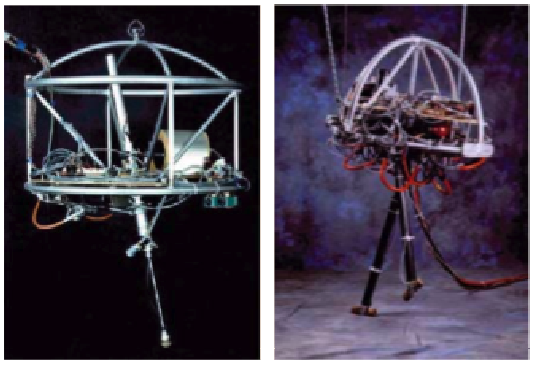

Figure 2: Left: Raibert's 3D one-leg hopper (1983). Right: the 3D biped (1989) [8].

The last group is represented by the so-called **passive dynamic walkers** [9], pioneered by McGeer who introduced the concept of natural cyclic behavior for a class of very simple systems: a plane compass on an inclined plane. It is the appropriate balance between increase of the energy due to the slope and loss at the impacts that produces stable walking. Recently, the principles of bipedal passive dynamic walkers have been used to develop powered bipedal walkers that walk with high efficiency in a more human-like way than the predecessors by exploiting natural dynamics [10] (see **Fig. 3**).

Figure 3: Passive dynamic walkers with extensions. On the left-hand side additional trunk, feet and knees (Denise 2004). On the right-hand side added semi-passive control for walking and running (Rabbit 2003) [11].

Though representing highly valuable technological achievements, the ability of these bipedal robots to compensate for disturbances and to walk versatilely and autonomously on very different terrains in a robust way still remains to be demonstrated. Due to nonlinear dynamics and complex design process, many existing underactuated systems so far are able to exhibit only one or two behavior patterns, and command a limited adaptability against environmental variations. Until now, there is no humanoid

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robot, possessing elastic, three-segmented legs and a torso, that is capable of changing its gaits within the same kinematic leg design. This is also due to the long overdue illusion that walking and running represent different mechanical paradigms. For a long time, walking had been simplified by an inverted pendulum model [12] and running by a spring-mass model [13]. Vaulting over stiff legs, however, cannot reproduce the mechanics of walking [14]. In reality, the fundamental gaits of walking and running are much less different than generally assumed. Recent work on bio-inspired robots suggests that elastic legs are crucial for both running and walking [15]. With the same compliant stance-leg behavior found in running, a bipedal spring-mass model can reproduce the stance dynamics observed in walking. Furthermore, it was shown that walking and running are only two out of many solutions to legged locomotion enabled by the bipedal spring-mass model.

3 Jena Walker II

Steps towards more human-like bipedal robot locomotion have been made with the development of Jena Walker II (see **Fig. 4**): a novel, elastic and biologically inspired, three-segmented robot that is attached at the trunk to a lateral guide. It is the first robot model that shows also in practice the realization of different gaits within the same kinematic leg design [16].

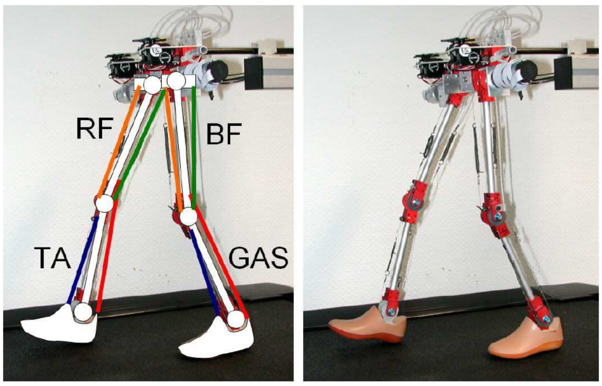

Figure 4: Three-segmented elastic legs of JenaWalker II with only one actuated joint in each hip module. On the left-hand side the used passive elastic structures are marked.

The modular robot system consists of rigid segments, actuated hip joint modules and adjustable elastic strings spanning including a prosthetic foot (SACH child foot, Otto Bock), shank and thigh. The four elastic structures represent the major muscle groups: *tibialis anterior* (TA), *gastrocnemius* (GAS), *rectus femoris* (RF) and *biceps femoris* (BF). The latter three structures are biarticular muscles spanning two joints, i.e. both ankle and knee joint. At the hip, two DC-motors introduce sinusoidal oscillations imitating the altering activity of the hip joint muscles during locomotion. The robot is capable of stable walking motions at different speeds.

Natural transition from walking to jogging was found at higher speeds in simulation and experiment by continuous variation of control parameters and without having to switch from one fully feedback controlled scheme to another for gait change. It was demonstrated that human-like behavioral diversity can be achieved by simple control and actuation considering morphological properties and that the control of legged locomotion can be largely facilitated by the intrinsic dynamics of the segmented body tuned by carefully designed elastic structures spanning the joints.

4 Important Gained Insights from Previous and Existing Projects

It has been realized that more than ever it is important to consider both control strategy and mechanical system simultaneously since the design of the controller and that of the morphology are inseparable from each other [2]. The goal of a such holistic view is to keep the control of the system as simple as possible by benefitting from the intrinsic dynamics of the mechanical system. Many other insights have enriched our developing strategies and techniques for adaptive autonomous human-like robots, aka. "intelligence by mechanics" respectively "mechanical intelligence" [17]. Some of them are presented below.

4.1 Use of springs in leg design

The use of springs in legged locomotion is generally accepted as important and has been promoted very early [18]. Particularly, three main uses are suggested:

1. pogo stick principle in order to bounce along on springs: helps to save energy and reducing unwanted heat production
2. return springs to halt the legs at the end of each forward or backward swing and start them swinging the other way: helps to save further energy
3. compliant foot pads to moderate forces at impact of feet with the ground: helps improving road holding by preventing vibrations.

The above three uses can be observed in animals and have also frequently appeared in existing robots, also in the author's group. Previous and existing projects have shown that there is a need for more use of springs in legged robots, particularly robots that are designed to run fast. Elasticity of legs, partially storing and releasing energy during contact with the ground, allows to achieve not only stable, but also rapid and energy-efficient locomotion.

4.2 Self-stabilization

The term "self-stabilization" refers to the observation that, after disturbances of the periodic locomotion pattern (e.g.

by ground irregularities), the center of mass returns to the limit-cycle trajectory without any (or only a minimal amount of) feedback control processing sensory information on the actual disturbance as observed also during simulation and experiments with Jena Walker II. In order to reduce the necessity for fully feedback controlled locomotion the stabilizing properties of muscle-tendon complexes and reflexes need to be introduced into the mechanical structure of the robot. Rapid adaptation to small unpredictable bumps in the ground can be taken over by passive compliance of the muscle-tendon system and the slack in the joints which is technically possible by employing electrical motors coupled to spring-damper systems.

4.3 Behavioral diversity due to morphological changes

The behavioral diversity can be significantly influenced by the dynamics induced by the interactions with simple motor action and the ground reaction force. For instance, the bipedal robot Jena Walker II demonstrates two gait patterns, walking and running, by exploiting nonlinear dynamics which are induced by the interaction of the elastic legs with the ground. The question arises how to manipulate morphological parameters such that different behavioral patterns can be generated on the fly. Phase-dependent activation of elasticities represents one out of many techniques to achieve behavioral diversity.

4.4 Compliant actuator design

As we have seen in the case of passive dynamic walkers, not only the mechanical structure but also the proper amount and principle of actuation is important. The main question is whether an actuation module needs to enable the adjustment of physical muscle stiffness, and whether we need complex hardware mechanisms to gain humans' performance. In [5] a good overview of the different actuator designs without focus on applications, though, is given. Certainly compliant actuator designs play an important role and have demonstrated so far a good and reliable functionality in many robots, such as the MACCEPA actuators [19] in the biped Veronica. But it is essential to have a look at the applications for which the actuators are to be designed and to note that the periodic ground contact creates different dynamics than in manipulation tasks.

Simulation of a four-legged robot revealed that the use of special bionic drives offers new possibilities of multimodal locomotion [20] without the need of either complex hardware integration or additional motors. The construction of the used drive is inspired by the functional principles inherent to the elastic and antagonistic muscle and tendon apparatus of the human arm [21] and has been tested thoroughly in the *Biorob* arm [22] (see **Fig. 5**). It is based exclusively on the application of the series elasticity in the drive in combination with an adequate positioning sensor system at the driving ends and in the joints. The actuation module can be considered as an extended series elastic actuator (SEA) offering, however, compared to SEAs, different possibilities of feedback and feedforward control and analysis. The deployed springs in each actuator have predefined mechanical constant stiffnesses, therefore the physical compliance can not be changed. But a dynamic adjustment of the equilibrium position of the springs, i.e. a different motor triggering, leads to a dynamic change in joint trajectory resulting in a behavior that is comparable to a real adjustment of the mechanical stiffnesses. We term this technique which enables multimodal locomotion "emulated spring stiffness" [20].

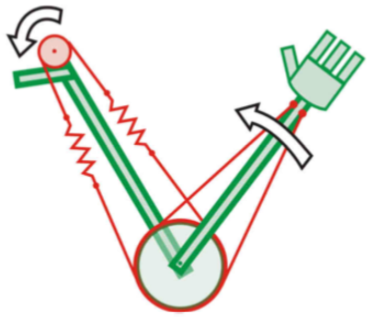

Figure 5: Actuation principle of the bionic drive used in the BioRob manipulator [22].

Furthermore, it should be noted that only the interplay of all joints and their actuators constitute the overall performance of one leg respectively foot.

4.5 Using computational optimization tools

In order to tackle with the problem of controlling nonlinear dynamics it is necessary to make use of appropriate optimization methods. Given a model with designated self-stabilization mechanisms, it is possible to identify the motor control parameters for the desired leg motions. Analysis of the main factors affecting the chosen objective function and a simple controller with preferably small parameter space are key factors that help reducing the number of iterations during the optimization process.

5 BioBiped Project

In order to further investigate the realization of different gaits without changing the kinematics of the bipedal robot, recently the BioBiped project has been launched, in which we collaborate with the Locomotion Laboratory in Jena. The aim is to build a humanoid robot that is as large as a child and can autonomously change its gaits without any lateral guidance. The important principles and approaches for the development of a such bipedal robot, as listed above, with focus on the design, actuation and control are currently being investigated and applied to a simulation model.

The legs consist of three segments, three biarticular structures, and five monoarticular structures (see **Fig. 6** and **Fig. 7**). The hip motors in the sagittal and lateral plane are actuated by bionic drives such as used in the BioRob manipulator [22] and recently in the four-legged robot [20]. The main purpose of their use lies in their visco-elastic property introduced between motors and joints for better damping in case of collisions or hits. Another highly valuable advantage of these drives is the possibility of pretension which also reduces the problem of backlash and play.

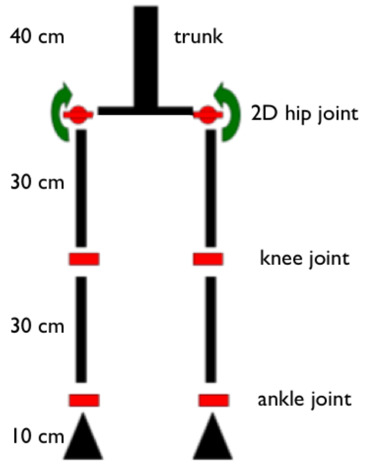

Figure 6: Front view of the structure of the novel bipedal model.

In order to feed the ankle and the knee joint with energy, i.e. support them during bending with motor power, the elastic structures *soleus* (SOL) and *vastus* (VAS) are actuated. The monoarticular structure TA in the shank and the biarticular structures RF, GAS, and BF are passive (see **Fig. 7**). For the first prototype we also consider a simple trunk that can tilt forwards and backwards. The number of DC motors in total amounts to nine.

In order to assess the performance of the used actuation modules including the underlying actuation principles and the integrated spring properties, the obtained sensory data from the joint encoders are compared with human experimental data from walking and running gaits. The classification of the gained results allows to adapt motor parameters and improve control strategies.

The sensory data provided by the encoders at the driving ends and in the joints helps comparing different control approaches, such as joint position control and motor position control, and supports the understanding of the role of the interplay of the passive and active elastic structures on the overall system dynamics. Force contact sensors at the feet heel and ball give us the opportunity to compare with experimentally observed data from human subjects resulting in the possibility to even better understand the principles underlying legged locomotion and tune our system such as the objective criterions can be achieved.

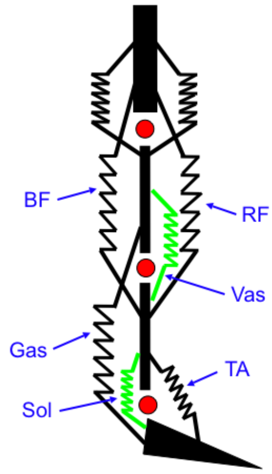

Figure 7: Side view of the mechanical design of the robot including the elastic structures spanning the ankle, knee and hip joint. The tensions marked in green color are actuated. All others are integrated as passive structures.

An inertial measurement unit in the trunk keeps track of changes in the linear acceleration and angular velocity of the robot. Furthermore instability detection and falling prevention by a simple yet robust and reliable balance technique based on a lunge module can be actively integrated in the low-level motion controller.

One essential task prior to manufacturing the robot incorporates the question of motor-gear selection. Obviously, answering this question is more tedious for an elastic robot with various biarticular and monoarticular structures spanning more than one joint than for a conventional stiff robot. Different approaches are thinkable; given useful experimental human data it is possible to carry out an “inverse dynamics” approach, i.e. to compute the motor torques and velocities that are necessary to realize given joint angle courses. Here, the knowledge about both the course of angles in the joints and the course of torques occurring during the stance and swing phase of locomotion is crucial.

Based on the recorded human experimental data the determination of the joint value intervals needed for different motions can be carried out more easily. From these data, for instance, it can be noticed as well that full knee extension as observed in the case of the passive dynamic runners never occurs during locomotion of healthy human subjects. In **Fig. 8** the joint values during running in the stance phase never reach $180°$.

Furthermore, the course of torques with respect to the angular positions needs to be known in order to capture the behavior of the corresponding elasticities working during stance and swing phase. Often it is desirable to approximate the torque-angle-relationship by some sort of function. This, however, is perceived as not trivial, particularly when looking at curves such as shown in **Fig. 9**. The occurring moments during stance and swing phase with respect to the angle course in the hip joint seem not to be describable by a mathematical function. Given the torque-angle course and joint-angle trajectories in the joints, the appropriate motor-gear-units can be identified by means of a corresponding model for the kinematics and kinetics of the robot (see **Fig. 10**). For further information we refer to [23].

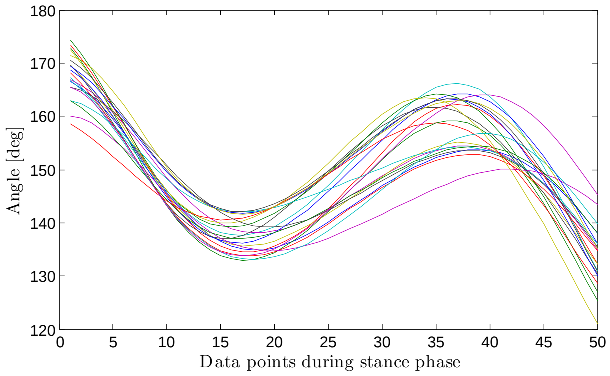

Figure 8: Angular positions of the knee joint during the stance phase in running gaits from 21 healthy human subjects.

6 Efficient Optimization of Walking

Walking optimization generally may be done in two different ways: on computational models or on the real robot. The direct use of any kind of gradient based or Newton type methods is difficult since only the objective funtion value disturbed by induced noise is available. There are three different groups of optimization methods designed for these kind of optimization problems. The first group summarizes the random search method or stochastic optimization methods. These methods use stochastic elements of heuristics to generate new promising candidates out of evaluated candidates. The second group consists of sampling methods: on the one hand direct optimization methods which only include the information if improvement is obtained or not and on the other hand sampling methods that include the objective function values also as quantitive information, e.g. the Nelder-Mead simplex approach or implicit filtering. All sampling methods have in common that new candidates are generated during their search for a maximum/minimum by exploring promising areas, or using bigger steps to find promising areas of the search domain. The third group of methods are the surrogate optimization methods. The optimization is not performed directly on the objective function but on an approximation of the function.

In previous joint work with the Locomotion Laboratory in Jena, two optimization methods were applied to the JenaWalker II [16]. The first sampling method is based on unconstrained implicit filtering. The motion is optimized for maximal speed, which leads to high torques of the hip motors, but results in a quite natural walking motion. Since the obtained increase in speed is associated to an increase of hip torques, in the second study the motion is optimized with the Nomad method for maximal speed constraining the hip torques. In the third study, the motion is optimized for minimal hip joint torques while the speed is limited to be higher than two thirds of the speed achieved in the second study.

One main disadvantage of sampling methods is the large number of iterations. This is even worse when carrying out hardware-in-the-loop optimization for the physical robot prototype. With respect to the longtime goal of facilitating online-optimization of walking motion whilst avoiding expensive function evaluations, it is recommended to use a surrogate optimization method. Based on recent developments in the field and using stochastic approximation of the underlying objective function and sequential quadratic programming, a surrogate optimization method was applied to the humanoid robot Bruno [24]. The optimization method consists in each iteration of a statistical approximation method that calculates a surrogate function of the original objective function. As a standard approach designed for deterministic black-box optimization problems, design and analysis for computer experiments (DACE) by Sacks et al. is widely used. The optimization procedure is implemented in Matlab and uses two standard additional toolboxes, the DACE toolbox and the optimizer SNOPT. It was demonstrated that efficient walking speed optimization can be obtained with a quite small number of function evaluations. In simulation of the developed model, though, it was also shown that a good initial starting parameter set is necessary such that the optimization yields good solutions before terminating.

7 Conclusions

For future applications desirable properties of robots operating in the real world comprise adaptivity, robustness, versatility, and agility among others. Bridging the gap between artificial and natural systems requires addressing many conceptual and technological challenges and involves interdisciplinary knowledge. In this paper we gave an overview of the current existing dominant groups of humanoid robots and presented novel strategies and insights based on previous and current projects leading to a series of novel biologically inspired robots extending further the capabilities shown by JenaWalker II. In this context, the recently launched BioBiped project was introduced and its main aspects and the so far noticed challenges have been discussed. It is necessary to design an intelligent mechanical system but also to develop a biologically inspired

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controller based on appropriate actuation and control algorithms such that the intrinsic dynamics of the system can be benefitted from. Such approach considering the mentioned principles and insights surely grants a deeper understanding of biological structures and processes and, most importantly, will guide the construction of novel types of robots of unprecedented diversity and behavioral characteristics.

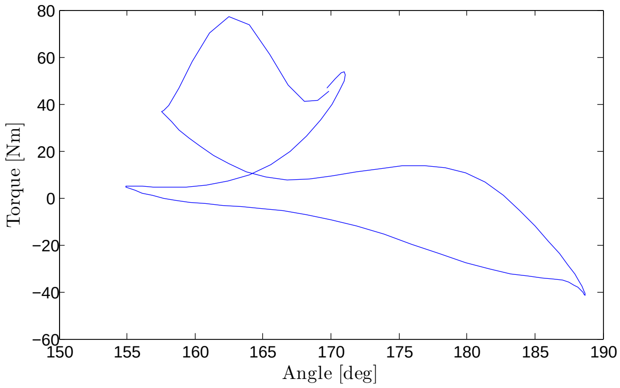

Figure 9: During stance and swing phase in running occurring torques with respect to the angular positions in the hip.

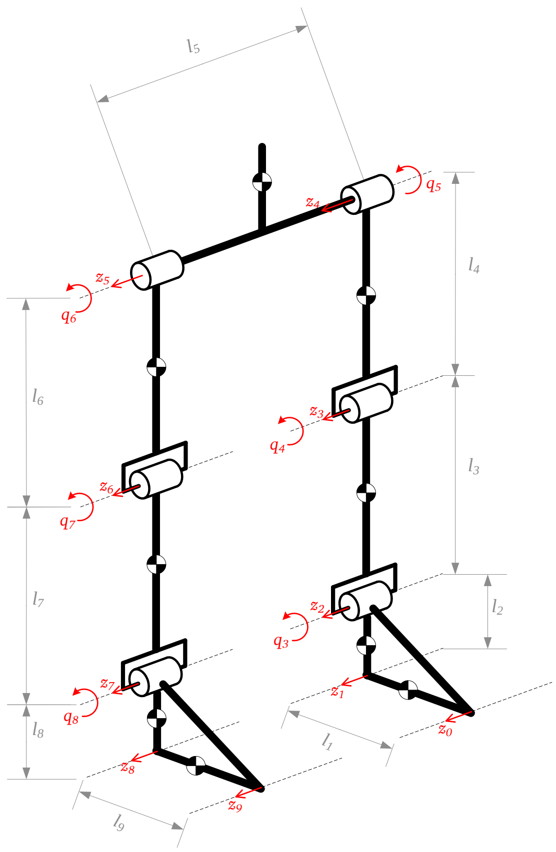

Figure 10: A simplified dynamic model for the robot.

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