Preprint of paper which appeared in the Proceedings of the
2010 IEEE International Conference on Biomedical Robotics and Biomechatronics

On the influence of elastic actuation and monoarticular structures in biologically inspired bipedal robots

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***Abstract*— Implementing the intrinsically compliant and energy-efficient leg behavior found in humans for humanoid robots is a challenging task. Control complexity and energy requirements are two major obstacles for the design of legged robots. Past projects revealed that the control complexity can be drastically reduced by designing mechanically intelligent systems with self-stabilization structures. Breaking through the latter obstacle can be achieved by the development and use of compliant actuators. Mechanical elasticity and its online adaptation in legged systems are generally accepted as the technologies to achieve human-like mobility. However, elastic actuation does not necessarily result in energy-efficient systems. We show that mechanical elasticity, although being worthwhile, can have negative effects on the performance of drives. We present a methodology that introduces both elasticity and energy-efficiency to a bipedal model. To this end, we report on the influence of monoarticular structures and demonstrate that these structures have the potential to both take us a step further toward the goal of realizing human-like locomotion and reduce the energy consumption.**

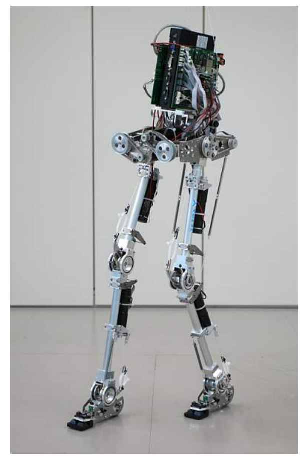

Fig. 1. BioBiped1: developed by TU Darmstadt, University of Jena and TETRA GmbH. Photo by A. Karguth/TETRA GmbH.

I. BACKGROUND AND MOTIVATION

A prerequisite for developing robots that are capable of human-like, energy-efficient movements is understanding the fundamental principles underlying legged locomotion [1], [2]. 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. Conventionally built robots such as “Asimo” are based on kinematic chains of rigid rotary joints and links. Joint movements are generated by stiff servomotors in the joints. This approach is responsible for poor energy-efficiency and stiff-legged gait. Such robots cannot exploit natural dynamics and self-stability of dynamic human locomotion. Furthermore, running movements on such systems are estimated to require a large amount of steady state power. Supplying power to such devices for several hours is well beyond the capabilities of current battery technology. Only an internal combustion engine can provide sufficient energy while still being small enough to be carried, with sufficient fuel, in a backpack. Consequently, proper actuation modules represent a key component of versatile and energy-efficient robots that move in a-priori unknown environments.

Recent research has focused more and more on actuators with adaptable compliance that can change joint stiffness in order to adjust the overall leg property, such as the MACCEPA [3] which was implemented in the biped “Veronica”. Although the on-the-fly adjustment of the spring stiffness is crucial and advantageous, this type of actuator also has some disadvantages: (1) its modeling is quite complex, and (2) it requires an additional servomotor in each joint where stiffness needs to be adapted. Besides, this type of actuator does not really resemble human muscles and to some degree it is desirable and has turned out as being efficient in functionality and promising to keep the appearance of robots close to humans.

A further concept to adjust joint stiffness and nominal angles was that of the pleated pneumatic muscles (PPAM) [4] as installed in the biped “Lucy”. Using artificial muscles represents a more elegant way to implement variable compliance. However, the use of pneumatics is not recommended due to mobility and other reasons.

On the other hand there are the developments of the passive dynamic walkers, pioneered by McGeer [5]. 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 [6]. These walkers, though, can not exhibit fast gaits like humans do. The installed energy supply is not sufficient and the actuation modules are not appropriately chosen for such movements. As a result, it can be concluded that both the mechanical structure and the proper amount and principle of actuation are important.

Until now, no robot can remotely approach the ability of humans to jump, run or perform other fast, explosive movements. The first robots that were capable of jumping, which

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is a prerequisite for the ability to run, emerged from Raibert's pioneering work [7] and consisted of telescopic springy legs. But biological limbs are not telescopic, rather they consist of an arrangement of leg segments where elasticity is localized at the joint level [8]. The very first robot that was capable of both energy-efficient and human-like walking and jogging was the bipedal robot "Jena Walker II", an elastic, biologically inspired, three-segmented robot. The modular robot system consists of rigid segments, actuated hip joint modules and adjustable elastic strings including a prosthetic foot, shank and thigh. At the hip, two DC-motors introduce sinusoidal oscillations imitating the altering activity of the hip joint muscles during locomotion. Natural transition from walking to jogging was found at higher speeds in simulation and experiment only 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 [9]. Due to the lateral guidance at the trunk, however, the missing energy supply for the knee and ankle joints during fast movements was not prevalent.

To conclude from the short foray into the state of bipedal robot designs, for fast human-like movements such as running or hopping it is urgently required that energy is actively supplied to the ankle and knee joints. In order to further investigate the realization of a human-like robot with human-like locomotion capabilities, recently the project BioBiped had been launched, in which the SIM Group of TU Darmstadt collaborates with the Locomotion Laboratory of University of Jena. The aim is to build a humanoid robot that is capable of running and walking motions within the same leg kinematics and autonomously changing its gaits without any lateral guidance. A picture of the first robot of a planned series is shown in Fig. 1.

One main aspect of this project among others is the energy-efficiency and effects of passive tendon-like structures. The use of springs in legged locomotion is generally accepted as important and has been promoted very early [10]. In fact, mechanical elasticity is a prerequisite for ballistic human-like movements, but does not necessarily result in low energy requirements. The built-in elasticities strongly interact with the actuator modules causing a higher payload. Therefore, it is important to study well before the development of a human-like robot where to integrate elasticities. Neglecting this issue during the design process may lead to an even higher energy consumption than detected in conventional robots.

In the following we present the simulation model of the bipedal robot. An inverse dynamics approach for the feed-forward control of the robot model is discussed in Section 3. In Section 4 the trade-offs of using elastic actuation are presented. Furthermore a methodology to address the perceived problem of higher energy consumption than in stiff systems is proposed. In this context, the potential utility of passive monoarticular structures in terms of reducing energy consumption in legged locomotion is explored.

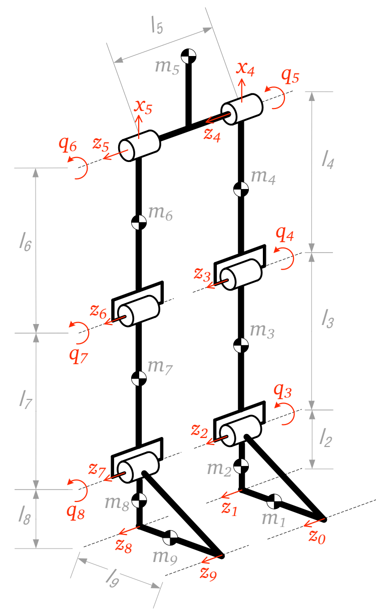

Fig. 2. 2D model of the bipedal robot.

II. SIMULATION MODEL OF THE BIPED

A. Kinematics and Dynamics Model

The simulation model presented here follows the robot design seen in Fig. 1, but does not exactly match the real robot model. The bipedal model consists of two segmented legs and a simple trunk that can tilt forwards and backwards. Each leg has three actuated joints in the hip, knee and ankle driven by bionic actuators that will be introduced in the next subsection, Section II-B. The corresponding kinematic and kinetic model of the robot in the sagittal plane is displayed in Fig. 2. The distances and proportions of the limb segments are based on human anthropometric data. The parameters of the links, such as length, mass, center of mass and inertia can be found in Table I and equal approximately the corresponding parameters of the real robot. For the estimation of the inertia we assume cylinders of radius r and height h, which equal the length of the links, aligned along the x-axis. The radius of the cylinders move in the range of 2 cm and 20 cm. The cylinders' principal moments of inertia are then given by $I_1 = \frac{m_1 \cdot r_1^2}{2}$, $I_2 = \frac{m_1}{4} \cdot (r_1^2 + \frac{l_1^2}{3})$, and $I_3 = \frac{m_1}{4} \cdot (r_1^2 + \frac{l_1^2}{3})$. Note that also the mass distribution very well corresponds to that of humans. The upper body weighs about 60% while the lower body including both legs amounts to 40% of the total weight of the robot.

B. Extended Series Elastic Actuation

For the actuation of the joints we make use of bionic drives consisting of a DC motor that is elastically coupled to the joint with antagonistic, elastic pulleys with progressive angle-torque characteristics, as illustrated in Fig. 3. The construction of the used drive is inspired by the functional principles inherent to the elastic and antagonistic muscle

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TABLE I

MODEL PARAMETERS: LENGTH, MASS, CENTER OF MASS AND INERTIA OF LINKS. THE INERTIA TENSOR I_c IS A $3x3$ DIAGONAL MATRIX AND COMPUTED AS $I_c = E \cdot diag$ WHERE E IS THE IDENTITY MATRIX IN $\mathbb{R}^{3x3}$. THE VECTOR $diag = \left(d_1,\, d_2,\, d_3\right)^\top$ CONTAINS THE MOMENTS OF INERTIA ABOUT THE x-, y-, AND z-AXIS.

i	l_i[m]	m_i[kg]	r_c[m]	I_c[kgm^2]
1	0.2	0.17	$\left(-\frac{l_1}{2},\, 0,\, 0\right)^\top$	$\left(3.4\cdot10^{-5},\, 5.84\cdot10^{-4},\, 5.84\cdot10^{-4}\right)^\top$
2	0.06	0.15	$\left(-\frac{l_2}{2},\, 0,\, 0\right)^\top$	$\left(3\cdot10^{-5},\, 6\cdot10^{-5},\, 6\cdot10^{-5}\right)^\top$
3	0.30	0.45	$\left(-\frac{l_3}{2},\, 0,\, 0\right)^\top$	$\left(9\cdot10^{-5},\, 3.4\cdot10^{-3},\, 3.4\cdot10^{-3}\right)^\top$
4	0.30	0.70	$\left(-\frac{l_4}{2},\, 0,\, 0\right)^\top$	$\left(3.15\cdot10^{-4},\, 5.4\cdot10^{-3},\, 5.4\cdot10^{-3}\right)^\top$
5	0.15	4.80	$\left(0.20,\, 0,\, -\frac{l_5}{2}\right)^\top$	$\left(5.7\cdot10^{-2},\, 5.7\cdot10^{-2},\, 9.6\cdot10^{-2}\right)^\top$
6	0.30	0.70	$\left(-\frac{l_6}{2},\, 0,\, 0\right)^\top$	$\left(3.15\cdot10^{-4}\, 5.4\cdot10^{-3},\, 5.4\cdot10^{-3}\right)^\top$
7	0.30	0.45	$\left(-\frac{l_7}{2},\, 0,\, 0\right)^\top$	$\left(9\cdot10^{-5},\, 3.4\cdot10^{-3},\, 3.4\cdot10^{-3}\right)^\top$
8	0.06	0.15	$\left(-\frac{l_8}{2},\, 0,\, 0\right)^\top$	$\left(3\cdot10^{-5},\, 6\cdot10^{-5},\, 6\cdot10^{-5}\right)^\top$
9	0.20	0.17	$\left(-\frac{l_9}{2},\, 0,\, 0\right)^\top$	$\left(3.4\cdot10^{-5},\, 5.84\cdot10^{-4},\, 5.84\cdot10^{-4}\right)^\top$
		7.74		

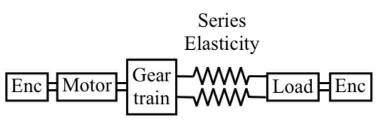

Fig. 3. Schematic of the extended series elastic actuator with only one motor.

and tendon apparatus of the human arm [11]. This actuation principle has already been tested extensively in a real manipulator, the "BioRob" arm [12], and a simulated animal-like four-legged robot [13]. It is based exclusively on the application of the series elasticity in the drive in combination with an adequate positioning sensor system at the motors and joints.

The actuation module can be considered as an extended series elastic actuator with only one motor, offering, however, compared to the original SEAs [14], different possibilities of feedback and feedforward control and analysis, although the mathematical models are similar. In contrast to SEAs, play and backlash can be reduced by pretension in the equilibrium position. In addition, angular sensors in the joints enable higher positioning accuracy.

Another advantage is the reduction of damages of the motors as the elasticity low-pass filters shock loads, protecting the gearbox from damage. In conventional robots additional masses are introduced by the motors that are directly coupled to the joints. The masses increase the effective mass during landing impact which lead to higher loading rates, potentially damaging the structures at higher speeds. This is a serious reason for such actuators not being useful for fast locomotion. One potential solution to this problem is therefore to shift the motors proximally and to decouple the motors mechanically from the rigid segments by tendons and springs. By using a progressive spring characteristic [15], [16], the joint becomes stiffer when accelerating and decelerating, having a positive effect on the performance. The joint torque measurement, however, is less accurate than in SEAs, because an inverse model of the spring characteristic is needed.

The SEA has already been deployed in several robots, such as in the "Spring Flamingo". Other prominent robots using SEAs are the bipedal robots Flame and TUlip [17]. However, these robots are not tailor-made for running or jumping, or in general fast movements that require high energy input particularly during ground contact.

Although elasticity in legs is crucial, it is quite important to keep a wary eye on energy-efficiency. We show in the next section that by using elastic actuation smooth motions and fast gaits can be achieved, but only at higher motor torques. A thorough analysis of how and where to place mechanical springs, whether in actuation modules directly or additionally in elastic structures spanning multiple joints, seems to be justified [18]. Only a prior analysis of the effects of these components and the interplay of all joints with the ground can guarantee a proper mechanical system that simplifies the control complexity and supports a reduced energy consumption. Fine-tuning and the support of additional elastic structures, i.e. parallel elasticities, allow the use of the above introduced drives in human-like robots due to the compliant actuation concept and the low power consumption. Further discussion on this matter follows in Section III. In the next section we present an inverse dynamics approach for the feedforward control of the robot model.

III. FEEDFORWARD CONTROL BY INVERSE DYNAMICS

Approaches with different degrees of difficulty and prospects of implementation are thinkable when working towards robots capable of human-like movements. In order to approach at best human-like movements, for the first investigations we make use of gait data that was recorded on a treadmill [19]. These data are consistent with other commonly cited sources.

Interest lies on the torques that need to be generated by the drives for the desired movements. For the computation of the motor torques and velocities we make use of time histories of sagittal plane joint angles and velocities of the hip, knee and ankle of a human subject during running. Joint angular accelerations are obtained from the joint velocities data by numerical differentiation. The used angular trajectories of hip, knee and ankle during a gait cycle are displayed in Fig. 4. A hypothetical 7 kg subject with leg length of 0.7 m, the data of the designed robot, is assumed to require the torques shown in Fig. 5. The displayed torques trajectories are normalized data of a human subject during running scaled with the body weight and leg length of the robot to narrow down the range of torques that at least is required for realizing similar movements as in Fig. 4.

Given these data it is possible to carry out an analytical inverse dynamics approach using numerical computing environments such as Matlab in order to determine the torques that are necessary to produce the specified motions. This

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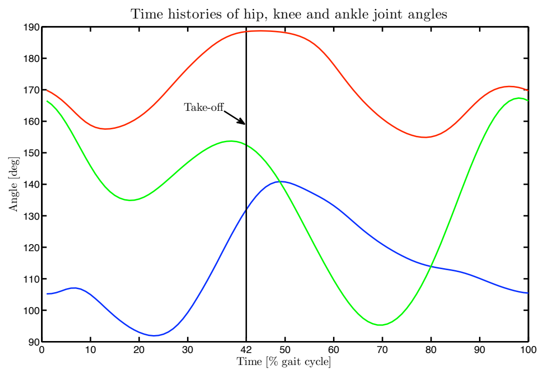

Fig. 4. Angular trajectories of the hip (in red), knee (in green) and ankle (in blue) of a gait cycle during running of a human subject with cycle time 0.7608 s, step frequency 2.6316 Hz, step length 0.9985 m, and flight time 0.0689 s.

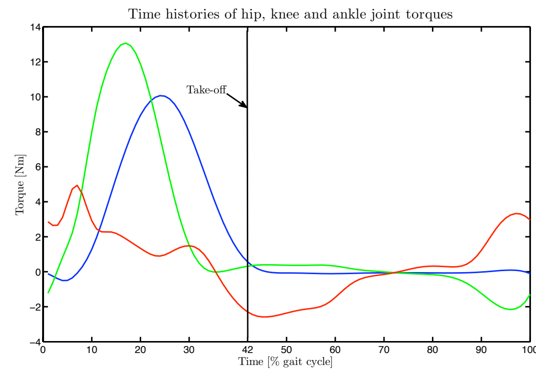

Fig. 5. Estimated torques trajectories for a 7 kg robot in the hip (in red), knee (in green) and ankle (in blue) mimicking the gait cycle during running of a human subject respectively producing the angular trajectories shown in Fig. 4.

means to compute from the joint angles q, velocities $\dot{q}$, and accelerations $\ddot{q}$ the necessary motor torques τ_m: For this computation we need to squeeze in an additional step to compute the unknown motor position trajectories $\theta(t)$. They can be determined by the torques in the installed springs τ_{El}:

$$\tau_{El} = K \cdot (\theta - q)$$
$$\Rightarrow \qquad \theta = K^{-1} \cdot \tau_{El} + q \ ,$$

where K describes the diagonal matrix containing the spring stiffnesses. The motor torques τ_m can now be determined by rewriting the equation of the motor dynamics with the second derivative of the motor positions $\ddot{\theta}(t)$:

$$\tau_m = J_m \ddot{\theta} + \tau_{El} \qquad (1)$$
$$= J_m \cdot (K^{-1} \cdot \ddot{\tau}_{El} + \ddot{q}) + \tau_{El} \qquad (2)$$

J_m represents the motor inertia and can be set to commonly used values for DC motors, also obtainable from the literature. For the missing information on the torques of the multibody system occurring in the joints τ_{El}, i.e.:

$$q, \dot{q}, \ddot{q} \in \mathbb{R}^n \rightarrow \boxed{\text{INV DYN of the rigid joint-link system}} \rightarrow \tau_{El} \in \mathbb{R}^n$$

we define the equation:

$$\tau_{El} = M(q)\ddot{q} + C(q,\dot{q}) + G(q) \ , \qquad (3)$$

where $M(q)\ddot{q}$ represents the symmetric, positive-definite joint-space inertia matrix, $C(q,\dot{q})$ is the vector of Coriolis and centrifugal terms, and $G(q)$ is the vector of gravity terms. For deriving the terms in Eq. 3 we use the Newton-Euler formulation. For the final computation of the motor dynamics it is required to compute the second derivative of the joint torques $\ddot{\tau}_{El}$ before. Note that this requires the double derivation of the trajectory τ_{El} and the fourfold derivation of the trajectory q.

Eq. 1 and 2 illustrate very well the necessity of further analysis in order to determine the relationship of τ_{El} and τ_m. It can not necessarily be argued that the additional term $J_m\ddot{\theta}$ directly leads to the motor torques being larger than the joint torques. In fact, this relationship is quite dependent on at least two factors, the existence of ground contact and the specified motion.

IV. Analyses of the Energy-Reducing Properties of Passive Monoarticular Structures

In the previous section we presented an inverse dynamics approach for the generation of human-like walking and running movements based on human experimental data. In this section now the focus lies on the power consumption of these movements. Particularly the performance of the stiff actuators and described elastic actuators in comparison is object of interest, i.e. comparing the torques and power consumption at the joints and driving ends. With the aid of monoarticular structures this comparison is further extended.

A. Elastically Actuated Two-Legged System Without Passive Structures

In the following we compare the performance of the stiff actuators and that of the elastic actuators for the hip joint. To this end, we generate by means of the previously defined equations the necessary torques at the driving ends and joints for the running motion displayed in Fig. 4.

Fig. 6 shows the computed torques of the hip joint of one leg for both rigid body system and elastically actuated system. The dotted line in each subfigure represents the torques of the elastically actuated system τ_m whereas the solid line represents the torques of the rigid joint-link system τ_{El}. As expected, the motor torques are slightly larger than the joint torques. The same holds true for the power consumption: during the two consecutive running steps it rises from 15.79 J to 16.54 J.

But obviously we do not want to miss the advantages of the bionic drives. Shocks are low-pass filtered and, thus, not directed to the elastic actuators in the full extent. Furthermore, the springs in the actuators can store energy and therefore, although at some points in time, during ground contact for instance, the elastic actuators have to work more than the stiff actuators, this load is released as soon as the legs take off the

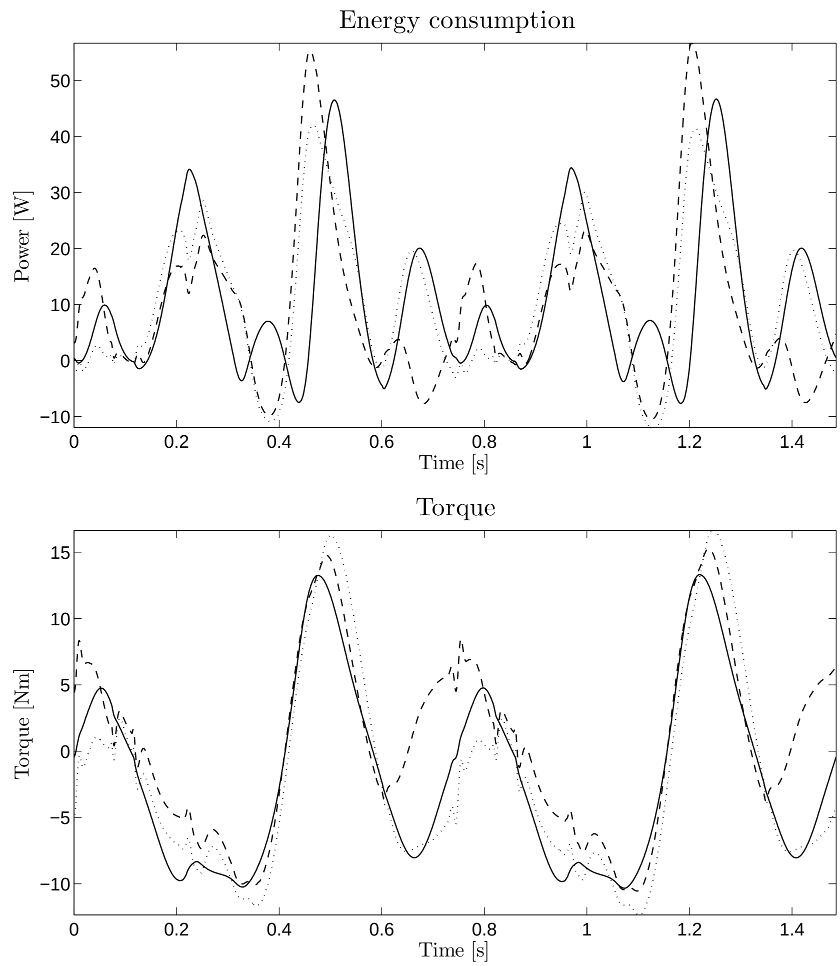

Fig. 6. Trajectories of the occurring torques and power consumption in the hip joint during two consecutive running steps. The solid line represents the trajectories of the stiff system, the dotted line describes the trajectories of the elastically actuated system and the dashed line describes the trajectories of the elastically actuated system supported by passive structures.

ground. In the long run the bionic drives surely guarantee a better and more reliable actuation of the system with respect to limited energy resources than a completely stiff system. Furthermore, it is possible to take off the loads by introducing passive elements as explained in the next subsection.

B. Elastically Actuated Two-Legged System With Passive Structures

As in [18] reported, poly-articular elastic mechanisms are a major contributor to the economy of locomotion. In animals these mechanisms are highly developed, sometimes spanning more than three joints. Biomechanically, these muscles have been ascribed the function of transferring energy from proximal to distal lower limb segments and are believed to have an inverse role in shock absorbency. It is concluded that unpowered passive elastic devices can substantially reduce the muscle forces and the metabolic energy needed for walking, without requiring a change in movement. Elastic devices can be much more effective if they span multiple joints, and therefore, anthropomorphic legged robots could benefit from these mechanisms, resulting in a dramatic increase in battery life.

Based also on the experiences with “Jena Walker II” the biobiped project aims at representing in each leg of the developed robot the functionality of the important muscle groups for walking and running motions, hence integrating as many as possible active and passive structures spanning one or more joints within each leg. In Fig. 7 a side view of the mechanical design of the robot is given, showing elastic structures that are also integrated in the real robot. The structures *Rectus Femoris* (RF), *Gastrocnemius* (Gas), and *Biceps Femoris* (BF) represent biarticular muscles, whereas *Tibialis anterior* (TA), *Soleus* (Sol), and *Vastus* (Vas) belong to the group of monoarticular structures. Biarticular muscles induce more complex dynamics because the force exerted on each spring is not only dependent on the angle of a single joint but also the angle of the other joint. With respect to the various roles of morphology these structures, however, have an advantageous effect. They mainly contribute to multimodal locomotion.

Due to the complexity of biarticular structures, for the intended analyses of energy consumption we made use of monoarticular structures. We modeled simplified hip extensors and flexors arranged in agonist-antagonist configuration.

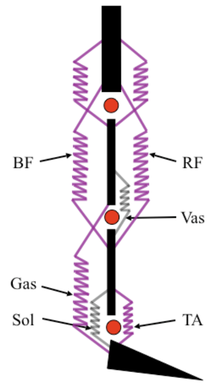

Fig. 7. The introduced elastic mechanisms mimic the biological muscle-tendon systems. Some span one joint, others two joints. The tendons marked in grey color are actuated, thus active structures. All others are integrated as passive structures.

One muscle supports the flexion of the joint, while the other supports its extension. From Fig. 6 it can be recognized that both power consumption and torques of the elastically actuated system can be decreased by means of these passive structures. The overall power consumption decreases to 14.44 J. The results indicate that, in practice, it is possible to use monoarticular muscle activation to transfer power between joints, which leads to an improvement of power efficiency in walking machines.

V. CONCLUSIONS

To the end of developing a humanoid robot with elastic, three-segmented legs and a torso, that is capable of changing its gaits within the same kinematic leg design, we presented a simulation model in the sagittal plane using an extended series actuation principle. It extends the well known series elastic actuator (SEA) principle and has several advantages over the conventional SEA. Using this actuator module for all actuated joints, we experienced slightly increased energy consumption when the model was fed with experimental human data compared with the corresponding stiff robot. We note that solely the presence of compliant actuation modules does not help to reduce the moments or velocities at the driving ends. Rather it is essential to study well where and how to introduce elasticities such that energy losses are avoided. We therefore explored the effect of monoarticular structures in the robot model and showed that they lead to reductions in the energy requirements.

The here presented study brings up lots of further questions. Experiments for running gaits with humans on a treadmill have shown that joint stiffness must be adapted during running. Obviously, for large running speed and human-like running behavior, some of the artificial muscles need to be activated phase-dependently in order to enable an online adaptation within the same step cycle. This will probably lead to a further reduction of energy consumption and thus needs to be investigated further in the future.

VI. ACKNOWLEDGMENTS

Parts of this research have been supported by the German Research Foundation (DFG) under grant no. STR 533/7-1. The authors thank Susanne Lipfert for providing human experimental data from walking and running.

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