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EXPLORING THE LOMBARD PARADOX IN A BIPEDAL MUSCULOSKELETAL ROBOT

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Towards advanced bipedal locomotion musculoskeletal system design has received much attention in recent years. It has been recognized that designing and developing new actuators with the properties of the human muscle-tendon complex is only one of the many tasks that have to be fulfilled in order to come close to the powerful human musculoskeletal system enabling the human to such versatile dynamic movements that no robot has been capable of replicating yet. But equally important is a technical implementation of the key characteristics of the human musculoskeletal leg system, segmentation and elastic leg behavior enabled by the mono- and biarticular muscles. So far, there has been an overwhelming consensus in biomechanics literature regarding the joint movements caused by biarticular muscles. In reality, however, they are responsible for an additional action during the second half of ground contact during fast dynamic motions in humans that has not yet been addressed by bipedal robot locomotion studies. Using BioBiped1, a bipedal compliant robot with human-inspired mono- and biarticular tendons, we demonstrate by means of a detailed multibody system dynamics simulation how this positive effect subserve energy-efficient dynamic 1D hopping motions and enables us to establish a novel bipedal locomotion model.

1. Introduction

Towards advanced bipedal locomotion musculoskeletal system design has received much attention in recent years. It has been recognized that designing and developing new actuators with the properties of the human muscle-tendon complex is only one of the many tasks that have to be fulfilled in order to come close to the powerful human musculoskeletal system enabling the human to such versatile dynamic movements that no robot has been capable of replicating yet.[1–3] But equally important is a technical implementation of the key characteristics of the human musculoskeletal leg sys-

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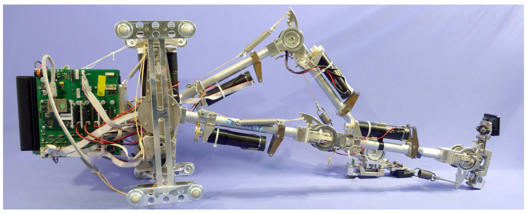

Figure 1. BioBiped1 robot: The first prototype of a planned series of robots with gradually increased bipedal locomotion capabilities.

tem: (1) segmentation and (2) elastic leg behavior. These assumptions have motivated the studies by Hosoda, Klein, Niiyama and their co-authors.[4–6] Several different versions of human-like musculoskeletal leg prototypes were built with the intention to reproduce the motion capabilities of the human musculoskeletal system. Another recently launched project aims at developing a fast, efficient and robust bipedal robot inspired by the musculoskeletal system of the ostrich.[7] All these studies have in common the integration of muscle-tendon like structures and their functionalities, inspired either by humans or animals.

A similar approach is followed by the BioBiped project to explore whether a more human-like leg functionality can be achieved by harnessing the intrinsic dynamics of a properly designed mechanical musculoskeletal motion apparatus based on the human lower limb system.[8] The BioBiped1 robot, depicted in Fig. 1, features a highly compliant tendon-driven actuation system using active and passive human-like elastic tendons. The nine mono- and biarticular muscles shown in Fig. 2(a) are known to contribute to the dynamic locomotion behavior of humans by sharing the necessary work in a highly "intelligent" and very well organized way causing a chain of energy transfer. Of particular interest are the biarticular muscles as they affect simultaneously the movements of two joints. In biomechanics literature there is an overwhelming consensus regarding the joint movements caused by these muscles. For instance, the muscle GAS, abbreviated for *Gastrocnemius*, is reported to extend the ankle and flex the knee joint. However, in Ref. 9 we could recognize a paradoxical action of the GAS tendon by means of forward dynamics simulation of the BioBiped1 multibody system (MBS) dynamics model. It acted as synergist extending the knee joint at knee angles above a specific position. After extensive search, we found a few biomechanics studies confirming this additional action during second half of ground contact in human locomotion.[10] Apparently, it was observed by Lombard already in 1903 and labeled the "paradoxical" function of biar-

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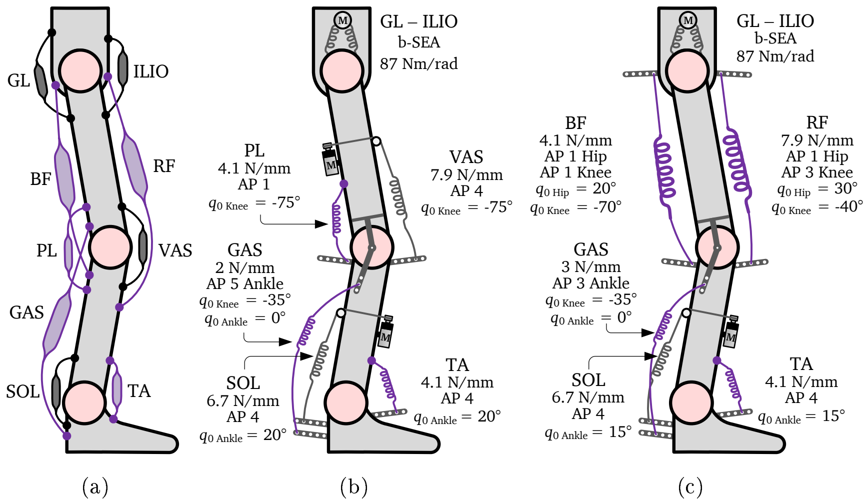

Figure 2. BioBiped1's musculoskeletal leg design (a) Essential human muscle groups during locomotion, tendons actuated by a motor in BioBiped1 are indicated by dark grey color; (b) locomotion model with the parameters used for the implemented structures (AP stands for the attachment point), studied in Section 3; (c) locomotion model suggested in Section 4, omitting the VAS motor.

ticular muscles. Interestingly, it has not yet been addressed by any bipedal robot locomotion studies.

In this paper we investigate the roles of the biarticular structures and elaborate on the reasons for this paradoxical behavior. Second we demonstrate the benefits rising from this understanding and analyze the impacts of this behavior on the interplay of the legs' active and passive tendons using forward dynamics simulation of the detailed BioBiped1 MBS dynamics model.[9,11] Finally, using these insights, we establish a novel bipedal locomotion model for energy-efficient dynamic 1D hopping motions.

2. Paradoxical Action of the Biarticular Structures

BioBiped1's legs are actuated by a combination of active and passive mono- and biarticular tendons mimicking the actions of the corresponding muscles that play an important role during human locomotion (cf. Fig. 2(a)). The monoarticular muscles comprise the antagonist-agonist pairs in each joint, *Gluteus Maximums* (GL) - *Iliacus* (IL) in the hip, *Vastus* (VAS) - *Popliteus* (PL) in the knee, *Soleus* (SOL) - *Tibialis anterior* (TA) in the ankle, and reported to strongly contribute to the task of power generation.[12] As for the technical realization in BioBiped1, the hip muscle pair is implemented by a bidirectional series elastic actuator (b-SEA), i.e. both flexion and extension of the hip joint are actively supported by a geared DC motor. For the knee and ankle joint it was decided to support only the extension movement by motor power. Thus, each knee and ankle joint is actuated by a combination of a unidirectional SEA (u-SEA) and its passive counterpart, as shown in Fig. 2(b). All remaining passive structures, including the biarticular structures, are integrated by a Dyneema tendon with built-in extension spring and can be detached or attached as desired. For more details regarding the actuator types and their implementations we refer to Ref. 9.

The biarticular muscles, of which the three most important are *Rectus Femoris* (RF), *Biceps Femoris* (BF) and GAS, in general are known to contribute to a proximodistal energy transport, i.e. from proximal to distal joints and in this way help to convert body segment rotations into desired translations of the body center of gravity.[13] While RF acts as combined knee extensor and hip flexor, BF, which is one of three muscles acting within the hamstrings muscle group, behaves exactly the other way. GAS extends the ankle and flexes the knee joint. However, this is a very common description of the above named muscles' actions and does not reveal their actually very complex, gait-dependent functionalities.

For instance, in human sprinting, the hamstrings muscle group has been found to be responsible for an additional action during the support phase.[14–16] Provided that the free end of the leg is guided, the hamstrings not only extends the hip, but also the knee joint.[10] The synchronous extension of hip and knee joint takes place for knee angles above -35 °[a]. Paradoxical muscle actions were also observed to be true for the GAS muscle during the last part of the ground phase during sprinting; there, GAS acted as synergist extending the knee joint at knee angles above -40 °.[17]

While it is an important insight that the roles of the biarticular muscles are manifold, there is only little information about the exact whole-body configuration and lever arms acting. Also, it would be interesting to investigate the nature of this phenomenon, whether it is gait-, phase- or configuration-dependent. Since detailed studies on human subjects are presumably required to fully understand the reasons for this paradoxical action, we will examine here this behavior by the laws of classical mechanics exemplary for the passive GAS tendon.

[a]A completely folded knee, resp. completely stretched knee, has an inner joint angle of -180 °, resp. 0 °.

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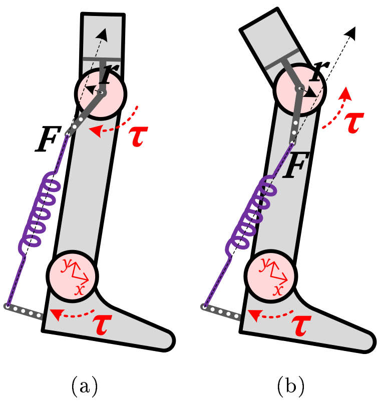
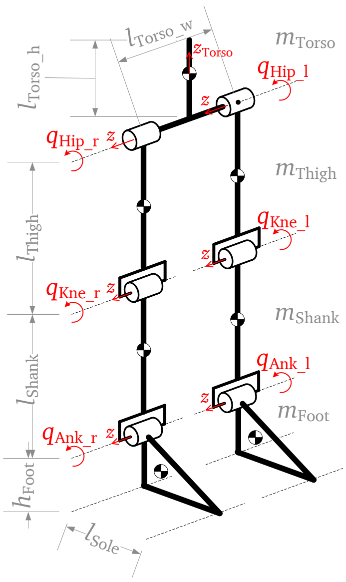


Figure 3. Paradoxical actions of the biarticular GAS structure can be strongly influenced by the manner the tendon is attached to the thigh: (a) GAS acts only as knee and ankle flexor; (b) GAS acts as ankle flexor and knee extensor.



Dimensions and Masses
$l_{\text{Torso\_h}}$=269 mm; $l_{\text{Torso\_w}}$=120 mm;
$l_{\text{Thigh/Shank}}$=330 mm; l_{Foot}=122 mm;
h_{Foot}=67 mm; l_{Sole}=165 mm
m_{Torso}=5.332 kg; m_{Thigh}=0.843 kg;
m_{Shank}=0.804 kg; m_{Foot} =0.342 kg

Figure 4. Main kinematics and dynamics data of BioBiped1's rigid skeleton.

Let us draw your attention to Figs. 3(a) and 3(b). In order to change a flexion into an extension movement of a joint, the torques acting on that joint need to be reversed in their direction. According to the definition of torque as $\boldsymbol{\tau} = \boldsymbol{r} \times \boldsymbol{F}$ where $\boldsymbol{r}$ and $\boldsymbol{F}$ denote the lever arm and force vector, respectively, the torque reversion requires either a reversion of the force or lever arm. In Fig. 3(a) the GAS tendon still acts as both ankle and knee flexor. The tendon force applied to the thigh and the load experienced by the lever lie on the same side of the joint. In Fig. 3(b) we have depicted a possible construction for the attachment of GAS to the thigh such that the lever lies on the other side of the joint and herewith causes reversed torques to extend the knee joint. The hinge joint mounted on the thigh passes on the tendon forces to torques acting on the knee joint. Such construction can cause permanently an extension movement of the knee joint. Obviously, it is also possible to reverse the direction of the force vector. In general, a such permanent functionality may turn out to be quite beneficial as we will evaluate in the next section.

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3. Evaluation of the Paradoxical Behavior of GAS by Open-Loop Controlled Trajectories for In-Place Hopping

In this section we will study the paradoxical behavior of the GAS tendon during in-place hopping motions in simulation.

3.1. *Simulation Model*

The simulation model of BioBiped1 consists of two levels containing the rigid joint-link structure, depicted in Fig. 4, and the underlying leg actuation design, displayed in Fig. 2(b). The robot is about 1.1 m tall in extended position and weighs around 9.3 kg. Its dynamic and kinematic parameters, such as link inertia and length, center of mass and mass of each link, were retrieved from the robot's CAD database. In order to detect collisions with the ground, each foot is assigned two designated point contacts, one each at the heel and the toe. The penalty-based contact model is described as a state machine that switches between normal force and stiction/friction. Details of the modular modeling approach and the foot-ground contact model by means of the self-developed libraries using MATLAB/Simulink and SimMechanics can be found in Ref. 11. The models of the actuators are discussed in detail in Ref. 9. The parameters of the contact model and geared DC motor are listed in Ref. 18. The parameters of the elastic transmissions, such as the stiffness, attachment points and rest angles of the implemented structures, are given in Fig. 2(b). In this study the model includes all monoarticular pairs in hip, knee and ankle joint and additionally the GAS tendon. In order to analyze the benefits of GAS as knee extensor, the tendon is attached to the thigh in the manner as shown in Figs. 2(b) and 3(b).

3.2. *Motion Generation*

Since hopping movements can be regarded as periodic oscillations between a flexed and extended leg configuration, we first select two desired leg configurations for the flexion and extension phase: $\boldsymbol{q}_{\text{flex}} = (q_{\text{Hip}},\, q_{\text{Kne}},\, q_{\text{Ank}}) = (26°,\, -63°,\, 13°)$, $\boldsymbol{q}_{\text{ex}} = (q_{\text{Hip}},\, q_{\text{Kne}},\, q_{\text{Ank}}) = (13°,\, -26°,\, -13°)$. The corresponding motor angles were then computed to compensate the gravitational forces in these configurations. For the generation of the trajectories we used the formula $y = A \sin(\omega\, t + \phi) + B$ with the amplitude A, angular frequency ω, phase ϕ and offset angle B. The desired fundamental frequency was set to $f_0 = 2\,\text{Hz}$. As low gain parameters for each motor PD controller we chose $k_{\text{p}} = 30$ and $k_{\text{d}} = 8$.

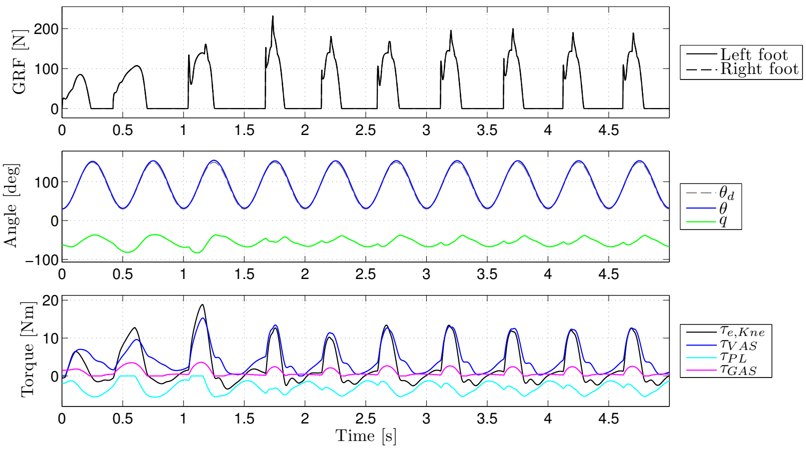

Figure 5. Simulation results with the locomotion model shown in Fig. 2(b): The top diagram displays the GRF; the middle diagram the desired and actual knee motor signal, i.e. θ_d and θ, and the actual knee joint angle q; the lower diagram shows the total knee joint torques, $\tau_\mathrm{e,Kne}$, and the single torques induced by all tendons coupling the knee (τ_VAS by the active VAS tendon, τ_PL by the passive PL tendon, τ_GAS by the passive biarticular GAS tendon).

3.3. *Forward Dynamics Simulation and Results*

The forward dynamics was computed in MATLAB/Simulink using the ode23 (Bogacki-Shampine) solver with variable step size, relative tolerance 10^{-3} and adaptive zero-crossing options. The outcome of this simulation were dynamic two-legged hopping motions with an average duty factor of 38.67 % and hopping height of 0.2218 m. The ground reaction forces (GRF) are displayed in the top diagram of Fig. 5. For these synchronous motions the GRF of both feet overlap. In the middle diagram the desired and actual knee motor signal, i.e. θ_d and θ, are displayed together with the actual knee joint angle q. The lower diagram is the most interesting, as it displays the total joint torques, $\tau_\mathrm{e,Kne}$, and the single torques induced by all tendons coupling the knee: τ_VAS by the active VAS tendon, τ_PL by the passive PL tendon, and τ_GAS by the passive biarticular GAS tendon. It can be recognized that GAS supports the actions of the knee motor by further extending the knee joint. In this leg actuation, however, this also results in higher PL torques, which in turn leads to higher VAS torques due to the interplay of the tendons. Therefore, with respect to an economical leg actuation design, it is thinkable to completely omit the knee motor for the extension, as for instance suggested in Ref. 19 for level-ground walking.

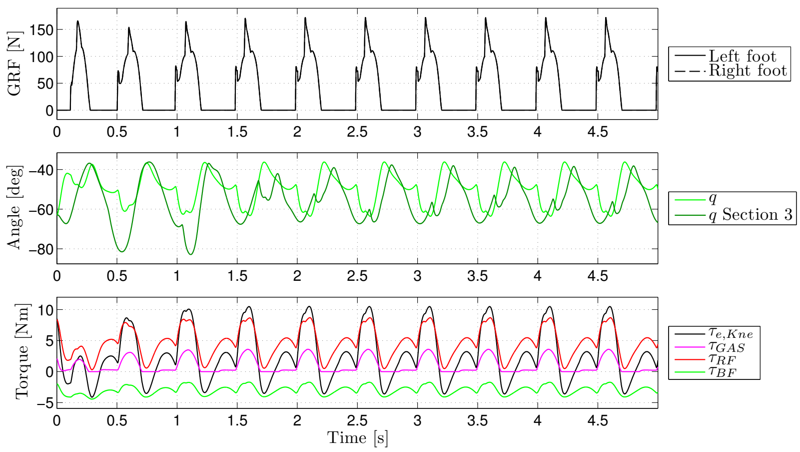

Figure 6. Simulation results with the locomotion model shown in Fig. 2(c): The top diagram displays the GRF; the middle diagram the actual knee joint angle q and for comparison that of the previous simulation; the lower diagram shows the total knee joint torques, $\tau_{\mathrm{e,Kne}}$, and the single torques induced by the passive biarticular tendons (τ_{GAS} by GAS, τ_{RF} by RF, τ_{BF} by BF).

4. Establishing a Novel Bipedal Locomotion Model

As one possible example, we suggest to include the RF and BF and to remove VAS and PL. The leg actuation design studied here is shown in Fig. 2(c). The same motor trajectories as in Section 3 are applied to this novel underactuated model, with the difference that the knee motions are now only influenced by passive biarticular tendons. As Fig. 6 indicates, this novel locomotion model is capable of highly dynamic two-legged hopping motions saving 62.59 % energy compared to the leg actuation discussed in Section 3 (see Table 1). With an average duty factor of 43.23 % and hopping height of 0.192 m, the motions are not as dynamic as those demonstrated in the previous section, but rather more regular when comparing the GRF patterns. The results suggest that dynamic hopping motions can be also performed without active knee extension benefiting from the paradoxical behavior of GAS. The only difference between the simulations of Section 3 and Section 4 concern the start of the simulation. The simulation model discussed in Section 3 was capable of starting directly from the ground, whereas for the robot model analyzed here we had to simplify the starting conditions by dropping the robot from 10 cm. By systematic optimization of the elastic transmission parameters in the ankle, an active lift-off from the ground is expected to be enabled even with this underactuated leg design.

Table 1. Energy consumption of the models discussed in Section 3 and 4.

Locomotion model	**Hopping height** [m]	**Hip** E [J]	**Knee** E [J]	**Ankle** E [J]	**Leg** $\Sigma\mathbf{E}$ [J]
With VAS (cf. Fig. 2(b))	0.2218	7.0526	304.3469	213.6929	525.0925
Without VAS (cf. Fig. 2(c))	0.192	8.5522	0	187.8801	196.4323

5. Conclusions

To our knowledge, this is the first paper in which the paradoxical action of biarticular muscles is discussed in the context of robot locomotion and exemplary analyzed for one muscle using the identified MBS dynamics simulation model of the BioBiped1 robot. The simulation results suggest to use the complex functions of these muscles beneficially to reduce the energy consumption. Also, the analyses raise the general question whether implemented human-like muscle-tendon structures have to act in conformity with biomechanical observations and suggestions. Rather, reported insights should be seen as valuable hints to enable the derivation of novel design guidelines that support dynamic robot locomotion.

Acknowledgements

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