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PAPER

A new biarticular actuator design facilitates control of leg function in BioBiped3

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Supplementary material for this article is available [online](#)

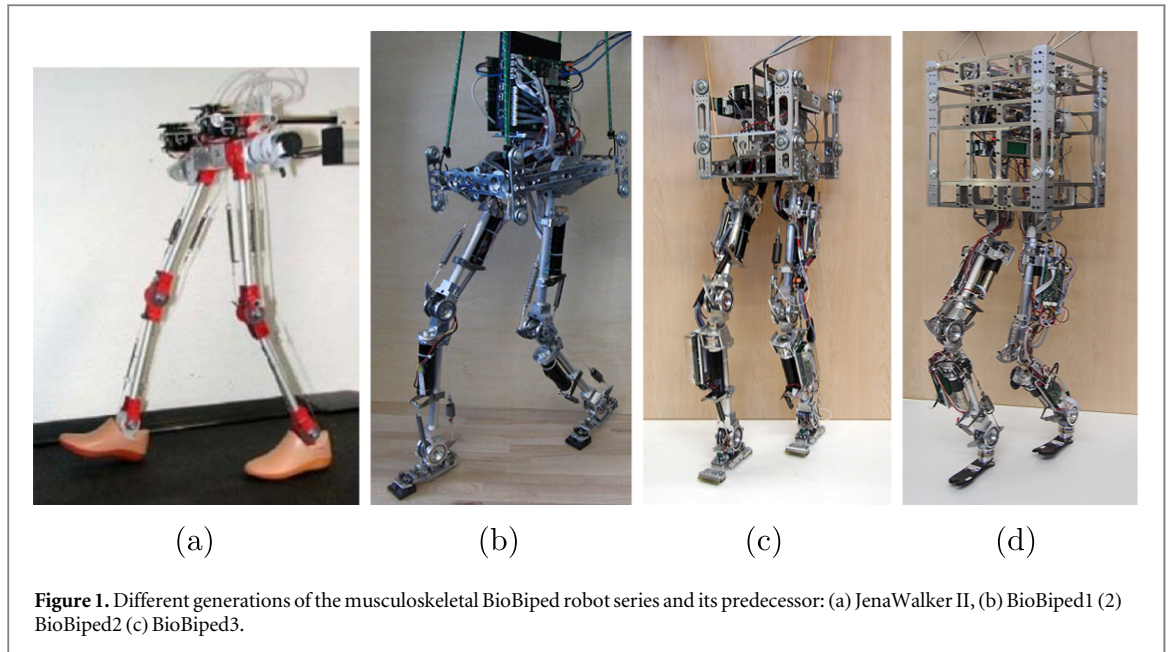
Abstract

Bioinspired legged locomotion comprises different aspects, such as (i) benefiting from reduced complexity control approaches as observed in humans/animals, (ii) combining embodiment with the controllers and (iii) reflecting neural control mechanisms. One of the most important lessons learned from nature is the significant role of compliance in simplifying control, enhancing energy efficiency and robustness against perturbations for legged locomotion. In this research, we investigate how body morphology in combination with actuator design may facilitate motor control of leg function. Inspired by the human leg muscular system, we show that biarticular muscles have a key role in balancing the upper body, joint coordination and swing leg control. Appropriate adjustment of biarticular spring rest length and stiffness can simplify the control and also reduce energy consumption. In order to test these findings, the BioBiped3 robot was developed as a new version of BioBiped series of biologically inspired, compliant musculoskeletal robots. In this robot, three-segmented legs actuated by mono- and biarticular series elastic actuators mimic the nine major human leg muscle groups. With the new biarticular actuators in BioBiped3, novel simplified control concepts for postural balance and for joint coordination in rebounding movements (drop jumps) were demonstrated and approved.

1. Introduction

A large number of roboticists and biologists explore bio-inspired design and control of legged robots. Advantages of having compliant legs are well accepted both in biomechanical studies of animal [1] and human locomotion [2] as well as in legged robot movement [3, 4]. Improving energy efficiency [5], robustness against perturbations [3, 5], achieving higher speeds [1], overcoming bandwidth limitations of actuators [6] and simplifying control [7], are some of the main advantages gained by compliant design. Pneumatic actuators [8, 9], compliant mechanisms

(e.g., leaf spring [4] or archery bow [10, 11]), series elastic actuators (SEA) with coiled springs [12], and emulated compliance (impedance control) with hydraulic actuators [13, 14] or electric motors [15] are the most common engineering solutions to achieve compliant legs in robots. One of the simplest leg morphologies based on the spring mass model of locomotion [16, 17] is the prismatic leg [3, 18]. With such a high level of abstraction, just some basic concepts of locomotion can be investigated. However, conceptual models like the spring loaded inverted pendulum (SLIP) [16] can also be utilized as templates for design and control of legged robots with more



complex body structure (e.g., segmented leg with two [4, 19] or three segments [20]). Although compliant legs seem to be crucial in legged locomotion there is certainly more we can learn from natural leg morphology when designing and controlling bio-inspired legged robots. With appropriate body design, more freedom in maneuverability alongside simplicity in control may be achieved.

In the BioBiped project⁸, we are working on designing biologically inspired robots with leg musculoskeletal structures similar to humans in order to apply locomotion concepts for representing human-like motor control in different gaits. The three-segmented legs of the BioBiped robots are equipped with compliant mono-/biarticular structures that mimic the main nine human leg muscle groups. They are implemented by SEA consisting of cables and springs in combination with electrical actuators or just passive springs.

In the first and second versions of BioBiped robots, monoarticular knee and ankle extensors besides hip muscle were active. However, biological studies on humans show that biarticular muscles have a key role in the single support phase of locomotion [21]. In addition, recent simulation studies by us and colleagues illustrate the importance of biarticular muscles in simplifying control in leg swinging [22] and postural balance [23]. Based on these evidences and experimental results with previous versions of BioBiped on hopping, active biarticular muscles have been introduced into the new version of our BioBiped robot, BioBiped3. With this new design we may adjust biarticular muscle parameters to (i) decouple rotational leg function from axial leg function in the stance phase, (ii) achieve swing leg control with biarticular

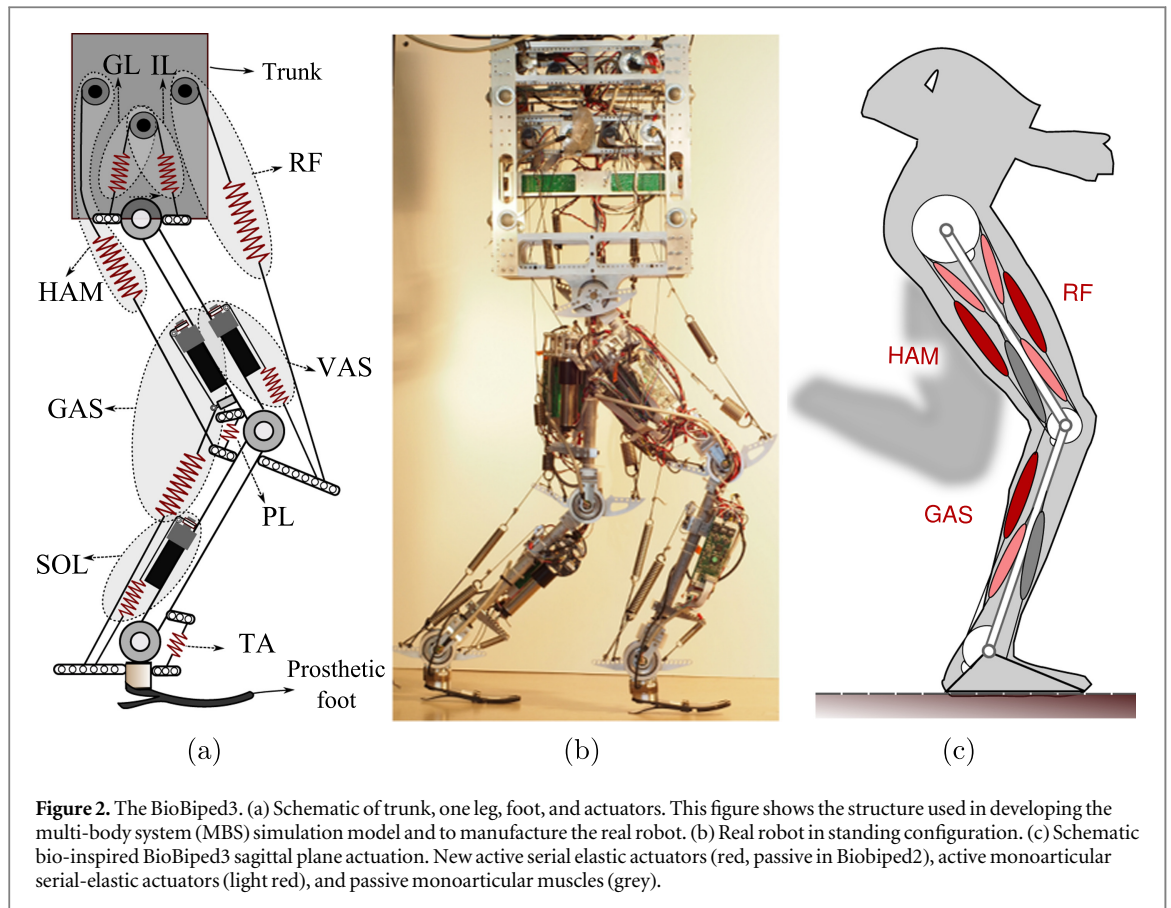
muscles decreasing energy consumption, and (iii) benefit from synchronizing segment movements based on the system dynamics [24, 25].

Recently, bio-inspired leg designs with musculoskeletal architecture were applied to legged robots [26–28]. As a result, novel robot designs with both biarticular and monoarticular actuators were realized [8, 26]. However, in these studies biarticular actuation is mainly employed for coordination between two joints and transferring energy from one joint to another. Here, we benefit from biarticular actuation in different aspects to facilitate the control of locomotion sub-functions (bouncing, leg swinging and balancing) [29]. Compared to pneumatic muscles, which are mainly used in bio-inspired bipedal robot designs [8, 26], SEA provides controllability in addition to elasticity.

2. BioBiped robot

The goal of the BioBiped project was to investigate and realize human-like stable locomotion in humanoid robots [30]. In contrast to conventional rigid bipeds, BioBiped robot series (shown in figure 1) are developed based on compliant musculoskeletal bipedal systems using SEA as replacement for biological muscles. In JenaWalker II (figure 1(a)), the predecessor of the BioBiped robot series, a single electric motor at the hip was utilized to actuate each leg in which energy is transferred to other joints through passive springs resembling human muscles. The BioBiped project aims at providing more advanced testbeds for experimental evaluation of hypotheses from biomechanics and investigate bio-inspired mechanisms' roles in different leg functionalities, required in locomotion. It offers the flexibility to change various mechanical configurations like spring stiffnesses,

⁸ www.biobiped.de



attachment points and the addition or removal of certain structures to compare different hardware setups. Also, it features a vast range of on-board sensors to not only allow for real-time control, but also provide additional data for monitoring and offline analysis. To reach aforementioned targets, we planned two steps, (i) development and application of conceptual models in a real robot mimicking human locomotion and (ii) searching for an appropriate mechanical structure in a robot to represent human muscle functions in locomotion. Therefore, in the BioBiped series of robots, the robot leg morphology (e.g., segments' length ratio) is designed based on human leg properties.

In order to achieve human-like motion performance on a robot with comparable power to weight ratio, SEAs with the potential to store and release energy in their elastic components are utilized. Placing the spring between gear head and the joint, results in passive protection of the gears and motors from impacts. In the new design, besides considering more flexibility in actuation and more precise measurements, we corrected some deviations from anthropomorphic characteristics of previous BioBiped versions.

2.1. Hardware structure

The BioBiped3 is a two-legged musculoskeletal robot with elastic joint actuation. Each leg is constructed as a

chain of three rigid segments (thigh, shank, and foot) connected by three 1-DOF joints (hip pitch, knee pitch, and ankle pitch) per leg (see figure 2 and table 1). The actuation is performed by SEA. For this, conventional DC-motors change the lengths of attached cables, which are in series with linear springs, to move the respective joints. The springs' stiffnesses are between 2.4 and 19.4 kNm^{-1} . Since with these SEAs we cannot change spring stiffnesses online during experiments we adjust the springs' rest lengths using motor position control. With this continuous rest length adjustment we can emulate different (or non-linear) stiffnesses. There is no limitation for changing the rest lengths if they are inside the maneuverable range of the joints. Physical constraints (e.g., mechanical lock at the knee for preventing hyper extension) may just reduce maneuverability and as a result will limit adjustable rest length ranges. The wire-driven actuation can generate only pulling forces similar to biological muscles. Thus, for mimicking the human musculoskeletal system, we use antagonistic actuators to pull the leg segments forward and backwards. A main advantage of the wire-driven actuation is the flexibility of the structure, e.g., to adapt the lever arms and springs. Currently, the power supply (24 V , 40 A) is external, but the robot is designed to have an on-board battery.

The torso of the BioBiped3 houses three actuators for each leg (figure 2(a)). One of them is used to

Table 1. Main characteristics of the BioBiped3 robot. Biarticular muscles RF, HAM and GAS refer to rectus femoris, hamstrings and gastrocnemius, respectively. Monoarticular muscles TA, SOL, VAS, GM, IL and PL represent tibialis anterior, soleus, vastus, gluteus maximus, iliopsoas and popliteus, respectively. The active cable transmission and the body design are shown in figure 2.

Dimensions and masses	
Segment lengths	$l_{\text{trunk}} = 0.37 \text{ m}$; $l_{\text{thigh}} = 0.33 \text{ m}$; $l_{\text{shank}} = 0.33 \text{ m}$; $l_{\text{foot}} = 0.16 \text{ m}$
Segment masses	$(m_{\text{trunk}} = 8.7 \text{ kg}$; $m_{\text{thigh}} = 2 \text{ kg}$; $m_{\text{shank}} = 1.2 \text{ kg}$; $m_{\text{foot}} = 0.4 \text{ kg}$
Foot	Ossur Flex Foot Junior from carbon fiber
Leg length	0.7 m (from hip to sole with extended leg)
Total mass	15.9 kg
Body CoM	0.01 m above the hip joint
Actuation	
Motors	12 maxon EC-powermax 22, brushless, 120 W, gear ratio 51:1
Active	SEA for RF, HAM, SOL, VAS, GL, IL, GAS
Passive	Passive springs for TA, PL
Stiffnesses	Adjustable
Sensors	
IMU	ADIS 16364 with 6 axes
Encoders	Motor positions: incremental and absolute joint positions: absolute
Force sensors	ATI F/T Sensor: Mini45; 6 axes sensor below ankle joint
Control system	
Hardware	13 custom made microcontroller boards; EtherCAT communication
Software	Orocos Real-Time Toolkit Robot Operating System (ROS)

actuate the hip joint. For antagonistic actuation, two cables are applied to the same hip motor, such that one of these cables is shortened depending on the direction of rotation. The other two motors are used to mimic the biarticular structures rectus femoris (RF) and hamstrings (HAM) and actuate both hip and knee joints. Each thigh houses two actuators, shown in figure 2(a). One actuator, which corresponds to the vastus (VAS) muscle, is used to perform the extension motion of the knee. The second motor of the thigh is applied to actuate the biarticular gastrocnemius (GAS) muscle. The shank houses one motor corresponding to the soleus (SOL) muscle for extending the ankle. The retraction motion (flexion) in knee (popliteus, PL) and ankle (tibialis anterior, TA) are implemented using antagonistic passive springs. The properties of the mechanical design of BioBiped3 are presented in table 1. More technical information about BioBiped3 is presented in [25]. Locking the motor position in a SEA mimics a passive spring while switching off the (backdrivable) motors results in damper-like behavior of the motors. Therefore, we can employ all muscles as (passive) spring, serial spring-damper or (active)

Table 2. Modifications in BioBiped3.

Problem	Solution
Flexibility in hip actuation (BioRob Arm technology).	Antagonistic SEA design
Foot design	Prosthetic foot
Low quality force sensors	Industrial force sensor
Passive biarticular muscles	Actuated biarticular muscles
Efficiency of motors	Brushless DC motor
Not anthropomorphic CoM	Larger and heavier trunk
Higher inertia of leg than trunk	Larger and heavier trunk

compliant actuators depending on their contributions in a specific task, except PL and TA which are just passive springs.

2.2. Software architecture

For the BioBiped3 robot, a flexible control infrastructure is implemented. Embedded electronics distributed among the robot read out position and force sensors and provide low-level motor control. All electronics are connected via an EtherCAT communication bus that allows reading sensory data and sending control commands at a rate of 1 kHz into/from a standard or embedded PC. Higher level control is implemented on this PC in C++ using an Orocos Real-Time Toolkit and the ROS Robot Operating System. Non-real-time applications for user interfaces, monitoring, and analyzing data from robot operation are implemented in Python.

2.3. Modifications in BioBiped design

Based on simulation and experimental studies on previous versions of the BioBiped robot, we considered the following modifications in the BioBiped3 design (a summary is presented in table 2).

- **Hip actuation:** We found the hip actuation mechanism based on pushing springs and a timing belt too inefficient and unpredictable. Furthermore, the maximum spring compression of the series elastic element was too limited and it was impossible to change the spring coefficients. The new design is based on the actuation concept of the BioRob manipulator in which one motor is considered to pull the lever arm in two antagonistic directions through two springs (see figure 2(a)). Thus, spring coefficients can easily be adapted and maintained.
- **Foot design:** The feet in BioBiped1 and BioBiped2 are bending under high ground contact forces. This results in plastic deformation and leads to limited capabilities. The new robot includes prosthetic feet. These are made from carbon fiber with a thin 2 mm rubber layer underneath. They are constructed to withstand high ground reaction forces, especially at impacts. In addition, they can easily be exchanged to test other prosthetic foot models.

- **Force sensors:** In the previous versions, the ground reaction force sensors evaluate the applied force based on the deflection of the feet. This approach is neither sufficient for precise calibration, nor deterministic due to the plastic deformation of the feet. The new construction includes off-the-shelf 6-axis force sensors (see table 1 for details) with sufficient capabilities to identify the applied forces.
- **Active biarticular muscles:** Simulation studies beside experimental results revealed that active biarticular structures can improve the performance of the robot. In the new design six motors are considered for each leg, instead of three in the previous versions. Two of the additional motors are applied to actuate biarticular thigh structures. In addition, the last motor can be used to actuate either the GAS or the knee flexor.
- **Efficient motors:** We replaced the brushed DC motors with 120 W brushless motors. As a result, we increased power density and actuation to suffice for the increased total weight of the robot construction.
- **Anthropomorphic CoM:** The overall center of mass of the previous robots was slightly below the hip rotation axis. This is not corresponding to the dynamical properties of the human body. For this reason, and also in order to house the additional actuators, the dimensions of BioBiped3 torso were increased. With these measures, the robot CoM shifted to above the hip rotation axis which is more anthropomorphic.
- **Higher trunk inertia:** The larger trunk containing more mechanical devices (e.g. six motors) also increased the inertia of the trunk leading to higher trunk inertia than leg inertia which facilitates swing leg control without losing the upright trunk orientation.

Among all these modifications, using active biarticular muscles is the crucial step that can facilitate robot control especially when mimicking human behavior in locomotion. In the next section, we elaborate on the significance of biarticular muscles for this based on simulation and experimental analysis.

3. Active biarticular muscles for simplified motor control

The design of the musculoskeletal system is the outcome of a long evolution [31]. The human musculoskeletal system is equipped not only with muscles spanning one joint (monoarticular muscles), but also with muscles spanning two joints, called biarticular muscles (figure 2(c)). The causes for these muscles pose a long-standing research problem. Leonardo da Vinci's lion robot (equipped with a central motor pulling strings) already illustrated what Cleland

[32] termed the 'ligamentous action' of biarticular muscles, namely that heavy muscles can be located proximally while transferring energy to the distal end of the limbs. This reduces inertia of fast moving limbs and thus contributes to efficient legged gait. Further, the joint coupling can increase the working range and improve the working point of monoarticular muscles [33]. Recent research could demonstrate that biarticular muscles can facilitate. (i) balancing [23], (ii) control of the leg swing phase [22, 34], and (iii) generating the whole running motion [23].

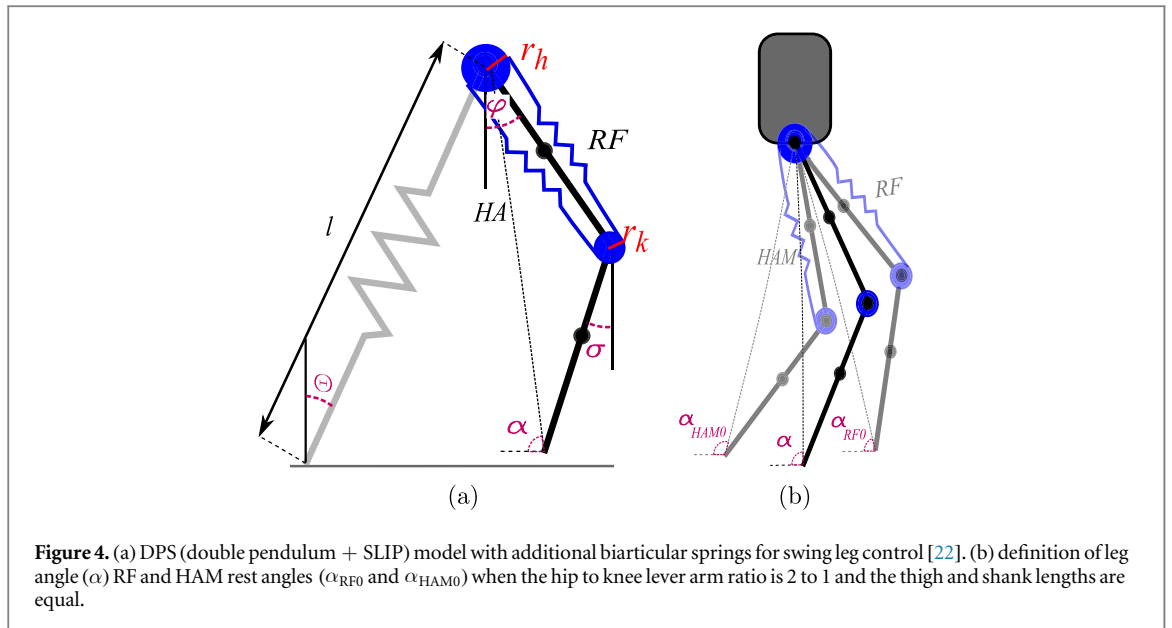
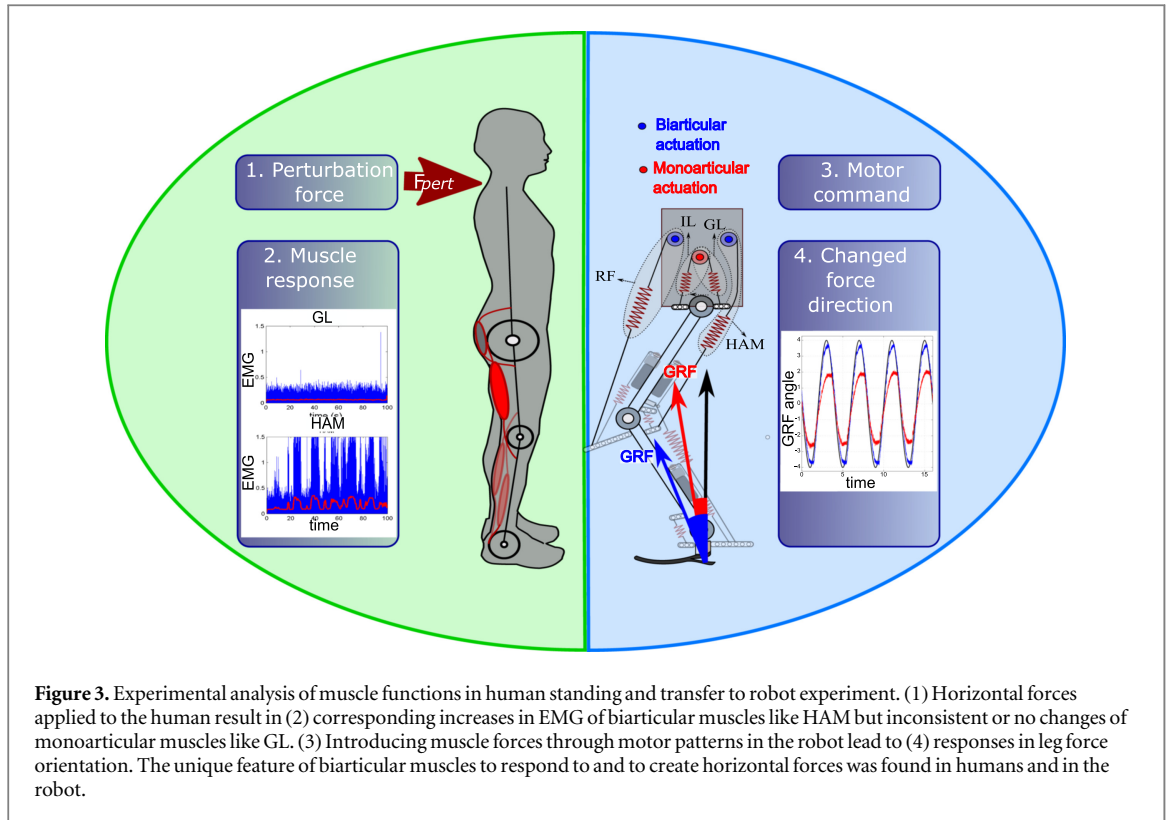
The following sections 3.1–3.4 motivate and outline human/robot experiments and simulations that substantiate the claim that may clarify whether biarticular muscles facilitate motor control. The corresponding results are shown in sections 4.1–4.4.

3.1. Stance leg

Biarticular muscles can generate considerable components of ground reaction force perpendicular to the leg axis (line from ankle to hip joint) in the sagittal plane [33, 35]. Perpendicular leg force is associated with postural control. A conceptual musculoskeletal arrangement with 2:1 hip to knee and ankle to knee moment arm ratios of biarticular muscles and equal thigh and shank lengths enables exclusive regulation of perpendicular leg force independent of the knee angle via biarticular muscles [23]. At the same time, the length change of the biarticular thigh muscles depends on the virtual leg angle (orientation of leg axis) with respect to the trunk. Biarticular thigh muscles do produce ground reaction force contributions matching those produced by hip torques in a model with telescopic leg. Moreover, when the biarticular thigh muscles are modeled as spring, they resemble a hip spring in a telescopic leg model [36]. This means that control concepts like the virtual pivot point (VPP) developed with models with trunk and massless telescopic legs [36] can be seamlessly transferred to models with trunk and massless segmented legs.

In recent human standing experiments we evaluated whether the conceptual musculoskeletal arrangement can explain muscle electromyography (EMG) activity [37]. Subjects were repeatedly exposed to a static external force applied at different positions of the body in the sagittal plane, and were instructed to hold their position. Assuming that the static torques can be balanced by either the action of biarticular muscles or by the action of monoarticular muscles, clear hypotheses can be drawn which muscles should increase in EMG activity. The concept of facilitating posture control using biarticular muscles in both human and robot experiments are illustrated schematically in figure 3.

To further elaborate on the function of biarticular muscles during locomotion, we implemented this conceptual design into a rigid-body model (trunk and



three-segmented legs). With the help of biarticular muscles, human running can be decomposed into a set of tasks which can be directly addressed [23]. This was demonstrated using a simple control scheme for a 7-link model (trunk and three leg segments with mass) capable of human-like bipedal running. The model was equipped with biarticular thigh and shank SEAs, and a knee SEA. The morphology, followed the conceptual morphology described above, is associated with elastic decoupling of axial and perpendicular leg function that enabled the task decomposition. These

results support the suggested role of biarticular leg muscles in achieving postural balance.

3.2. Swing leg

Biarticular muscle force shows a characteristic pattern during the swing phase in human walking [21]. In [22], we combined the spring-loaded inverted pendulum (SLIP) model [16] for the stance leg with a double pendulum model representing the swing leg which is called DPS (double pendulum +SLIP, depicted in figure 4). It was shown [22] that tuned biarticular

springs can replicate the muscle forces during the swing phase while at the same time the double pendulum reproduces the kinematic pattern of the human swing leg motion. Given adequate initial conditions of the swing leg segments at the beginning of the swing phase, the parameters of the biarticular springs (e.g. their rest lengths) may be set prior to the swing phase to yield human-like swing leg motion. Thus, in a robot with locking mechanism, the spring rest length can be adjusted and locked at takeoff to have a completely passive swing leg in walking.

In order to evaluate the applicability of this swing leg control, we tested it in the BioBiped multi-body model for forward hopping. In [20], we applied the virtual model control to mimic a virtual spring between the hip and the foot for axial leg function (bouncing) control and velocity based leg adjustment (VBLA) [38] for swing leg control in forward hopping. Since the focus is on swing leg adjustment, to handle posture control the upper body is physically constrained to be upright, similar to the alternate hopping experiment on a treadmill⁹. During the flight phase the knee actuator adjusts the leg length with controlling the knee angle (to 146° inner joint angle in this experiment) using a PID controller. In VBLA, the monoarticular hip actuator adjusts the orientation of the leg axis (from hip to ankle) with respect to the horizontal axis (leg angle α), computed from the CoM velocity vector. The control quality was tested by starting from hopping in place, switching to forward hopping with a certain speed and returning to zero speed, by changing the VBLA parameter [20].

In the here presented BioBiped3 simulation study, the monoarticular hip muscles are removed during the flight phase and the swing leg is controlled using adjustable biarticular (RF and HAM) thigh springs. The biarticular thigh muscles (represented as a SEA in BioBiped3) work only if the SEA spring is loaded. With hip to knee lever arm ratio of 2 to 1 for these muscles and equal thigh and shank length, this requires that the leg angle α is above (or below) a corresponding rest angle as shown in figure 4(b), i.e. $\alpha > \alpha_{RF0}$ for RF and $\alpha < \alpha_{HAM0}$ for HAM. To implement this approach in the BioBiped3 model, we adjust these two rest angles to achieve a certain speed. Therefore, similar to the passive rebound experiment (section 3.4), by locking motor positions during the swing phase, all muscles (except GL/IL which are removed) are simplified to become passive springs and the robot behaves like a passive elastic structure. In this control strategy, to reach a certain speed, the thigh biarticular muscles' rest angles are adjusted once (with a step-like signal at the first takeoff after getting a new speed) and kept until a new desired speed is set. In contrast to VBLA, we do not need to measure the CoM velocity to find the desired angle of attack. Therefore, no sensor is

required except the foot force sensor for detecting the takeoff.

3.3. GRF direction control experiment

In order to demonstrate the advantages of using biarticular HAM and RF muscles for stance leg control (compared to monoarticular IL and GL muscles), we conducted GRF direction control experiments in the BioBiped3 robot during stance. Each experiment includes either (i) active biarticular thigh (HAM/RF) SEAs, or (ii) active monoarticular hip (IL/GL) SEAs. Hip to knee moment arm ratios for both biarticular SEAs are about 2:1. A sine trajectory is set as the desired GRF direction for both legs. The robot trunk is constrained in a frame and could only move up or down. IL/GL SEA motor is off (acting as a damper because the motor is back-drivable) during the experiment of controlling GRF direction with biarticular SEAs. Biarticular SEAs are removed during the experiment of controlling GRF direction with IL/GL SEAs. In both cases, all other joints' SEAs (except knee VAS) act as passive springs (fixed motor position control). With ankle force sensor feedback, a simple PID controller is implemented for active motors. PID parameters were tuned for different experiments, separately.

To investigate how the knee angle affects the results, the experiments are performed in two different knee configurations:

- (i) static (standing): VAS motor shaft position is fixed. VAS act as a passive spring. Knee angle is about 26 degree during the experiment.
- (ii) dynamic (squatting): VAS motor shaft position is controlled by a sinusoidal wave with frequency 0.125 Hz. Knee angle changes from 14 degree to 41 degree during the experiment.

3.4. Joint synchronization with biarticular structures

In order to achieve maximum jumping performance, a sequential extension of leg joints from proximal to distal is required [39]. Using an articulated physical model of the vertical jump, Bobbert *et al* [40] showed that the timing of the GAS activation is critical to obtain a maximum effect. By transferring energy between joints, biarticular RF and GAS helps the monoarticular extensors (at hip and knee) to remain active until take-off without damaging the joints [39]. In addition, in human hopping in place, GAS muscle activation provides a rapid ankle extension which has a large effect on the vertical velocity (by translating the stored energy into velocity) resulting in greater hopping heights.

Here, we design a vertical passive rebound experiment with the BioBiped3 robot to analyze the GAS rest length effect on synchronizing ankle and knee joints and energy management at impact. In this experiment

⁹ See https://www.youtube.com/watch?v=ew_qhFEh6TM

we drop the robot from a certain height (h_0 of 7.5 cm and 15 cm, two trials for each height) and investigate the role of the GAS in recoiling the energy to the system to gain higher hopping height after rebounding. All motors are locked in fixed positions, representing muscles with passive springs having fixed rest lengths and stiffnesses. GAS muscle is also passive, but the rest length is changed from one trial to the next. We decrease the GAS rest length (l_0^{GAS}) from 0 to -5 cm while $l_0^{\text{GAS}} = 0$ cm gives no interaction from GAS. Therefore, the robot mimics a passive structure using motor position control.

4. Results

In this section we present the results of the different human/robot experiments and simulations outlined in section 3. In section 4.1, a human perturbed standing experiment shows the important contribution of biarticular muscles in posture control through the stance leg. Then, DPS and BioBiped MBS simulation models are employed in section 4.2 to generate stable walking and forward hopping using passive biarticular thigh muscles for swing leg control. GRF direction control experiments with BioBiped3 in section 4.3 show how biarticular muscles help facilitate leg force control. Finally, the passive rebound experiment with *BioBiped3* in section 4.4 demonstrates synchronization of adjacent joints by the biarticular GAS muscle.

4.1. Human perturbed standing experiment

In the perturbed standing experiment the EMG is utilized to identify the muscle contribution to perturbation recovery. Sample responses for monoarticular GL and biarticular HAM muscles are shown in figure 3 (see more details in [37]). The EMG of the biarticular muscles increased consistently, as expected in the theoretical model. Monoarticular muscles did not show a consistent EMG response. This indicates that biarticular muscles are the main contributors in the production of required torques to withstand the external force. This is in line with previous findings on the role of biarticular muscles in postural control [33, 35]. The contribution of monoarticular muscles for balance control needs further investigations. For instance, in our static experiment they might be used to fine-tune the static joint torques due to deviations of human muscle arrangement from conceptual design. We take advantage of these insights in the design and control of the novel BioBiped3 robot (see section 4.3).

4.2. Swing leg control

The addition of passive biarticular thigh muscles with an appropriate set of rest length and stiffness to the DPS model can produce human-like leg kinematics during swing phase of walking [22]. Figure 5 shows

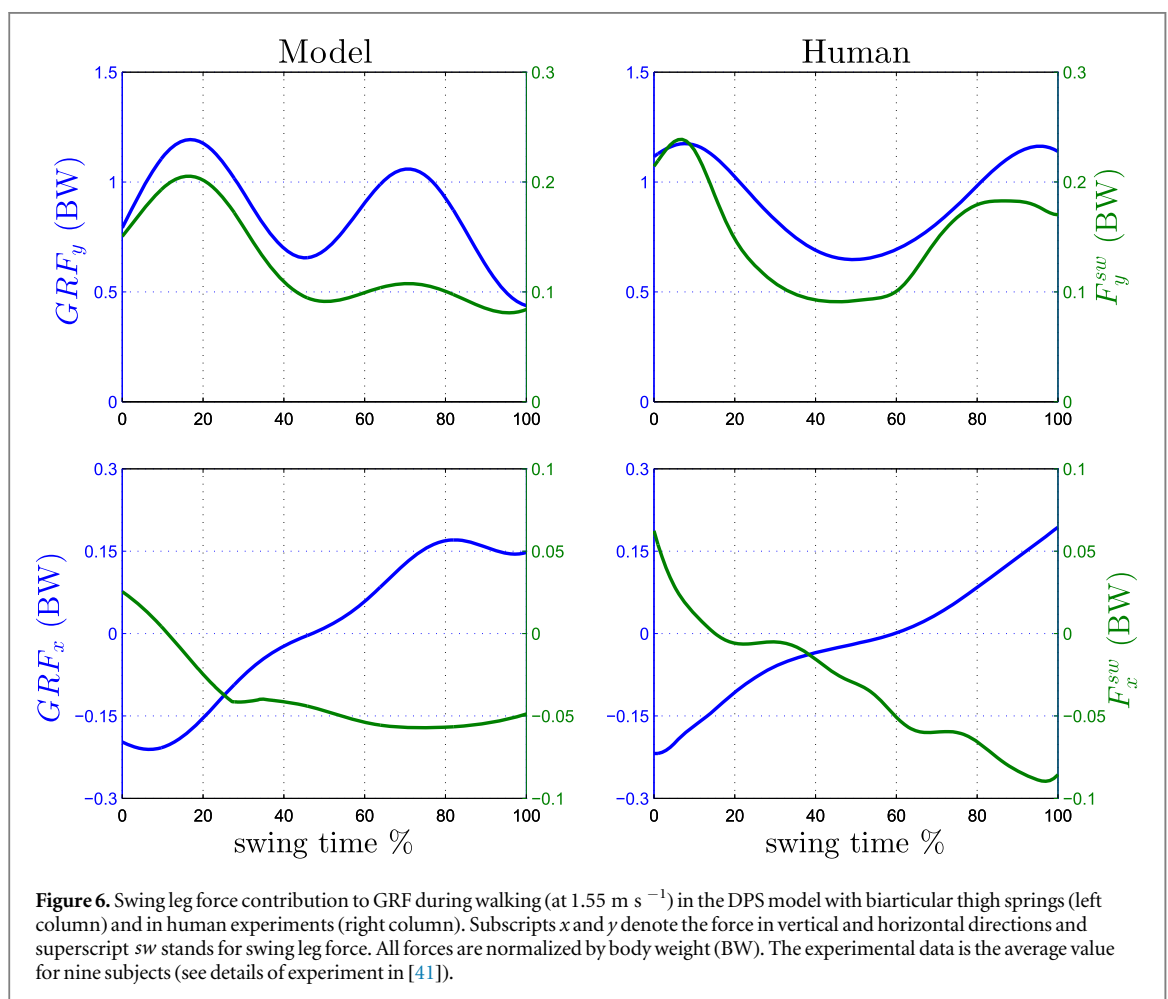
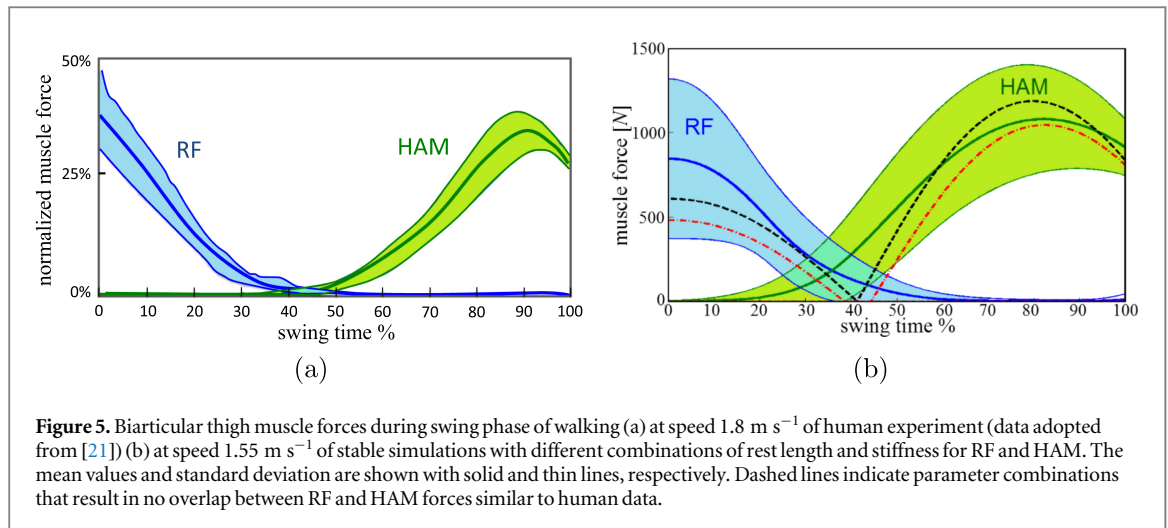
that the biarticular muscle force patterns in the simulation model are similar to human biarticular muscles (during the swing phase), and stable walking can be achieved in a large range of biarticular thigh muscle parameters. Although the overlap between working regions of RF and HAM in simulations is more than the negligible (with very low forces) range in the human experiments, there are sets of parameters which result in no overlapping. Two samples of such behavior are depicted with dashed lines in figure 5; red with no-force region from 38% to 44% of swing time and black with no-force moment at 41% of swing time. In the BioBiped3 robot, the ability to adjust the biarticular muscle rest length enables us to test this simple swing leg control strategy for different gaits in hardware.

Besides providing a certain angle of attack and ground clearance, the swing leg also has a noticeable contribution to the GRF [41]. As can be seen in figure 6, during the swing phase of human walking, swing leg force is in phase with the GRF in vertical direction while it is out of phase in horizontal direction. Swing leg force magnitude is about 25% of GRF at regular walking speeds. This means that the swing leg partially supports the vertical GRF and with counteracting in the horizontal direction helps balancing the upper body. Similar contribution of the swing leg movement in GRF can be observed in the DPS model equipped with biarticular passive springs having appropriate stiffness and rest angles. Therefore, adjustment of biarticular muscles (springs) in the swing leg will also support GRF control and balancing.

The same simple control approach for leg swing like in the DPS model, applied to the BioBiped MBS model for forward hopping, results in stable forward hopping with adjustable speed (as explained in section 3.2). Figure 7 shows the result of changing hopping speed using this technique. The simulated robot movement starts from zero horizontal speed (hopping in place) and we tune the RF and HAM rest lengths to certain values (shown in table 3) which results in moving forward. Note that these parameters are adjusted once and are kept constant until the next speed change. With that we achieve forward hopping at 1.5 m s^{-1} speed with passive swing leg adjustment. After five seconds both muscles rest lengths are decreased (table 3). This results in larger (smaller) working region of RF (HAM), which changes the angle of attack and swing leg angular velocity to return to hopping in place. Unlike feedback control for swing leg adjustment (e.g., VBLA), here we just set the biarticular muscles' rest angles to achieve different speeds and even changing the gait.

4.3. GRF direction control in BioBiped3

In this section, we show the results of GRF direction control during standing and squatting. As both legs are operating in parallel, only the results of one leg are



presented in figures 8 and 9. The first experiment was the static standing. In figure 8 (left), tracking of the GRF angle with monoarticular and biarticular muscles without changing the leg configuration is shown. Control with biarticular muscles is more precise in adjusting leg force direction than control with monoarticular ones. Note that, if the monoarticular muscle force increases to improve the tracking of GRF direction, the resulting axial leg forces (due to cross-talk) interferes with leg length control (through knee

angle control with VAS). This means that VAS control would need to compensate for the cross-talk to preserve axial leg configuration. In order to control the GRF direction with monoarticular muscles and also keeping the static condition (without movement), additional energy in the knee actuator is needed. With monoarticular muscle control, not only the tracking error of GRF direction in control is much higher than that in control with biarticular ones but also variations in the GRF magnitude and in the knee angle are much

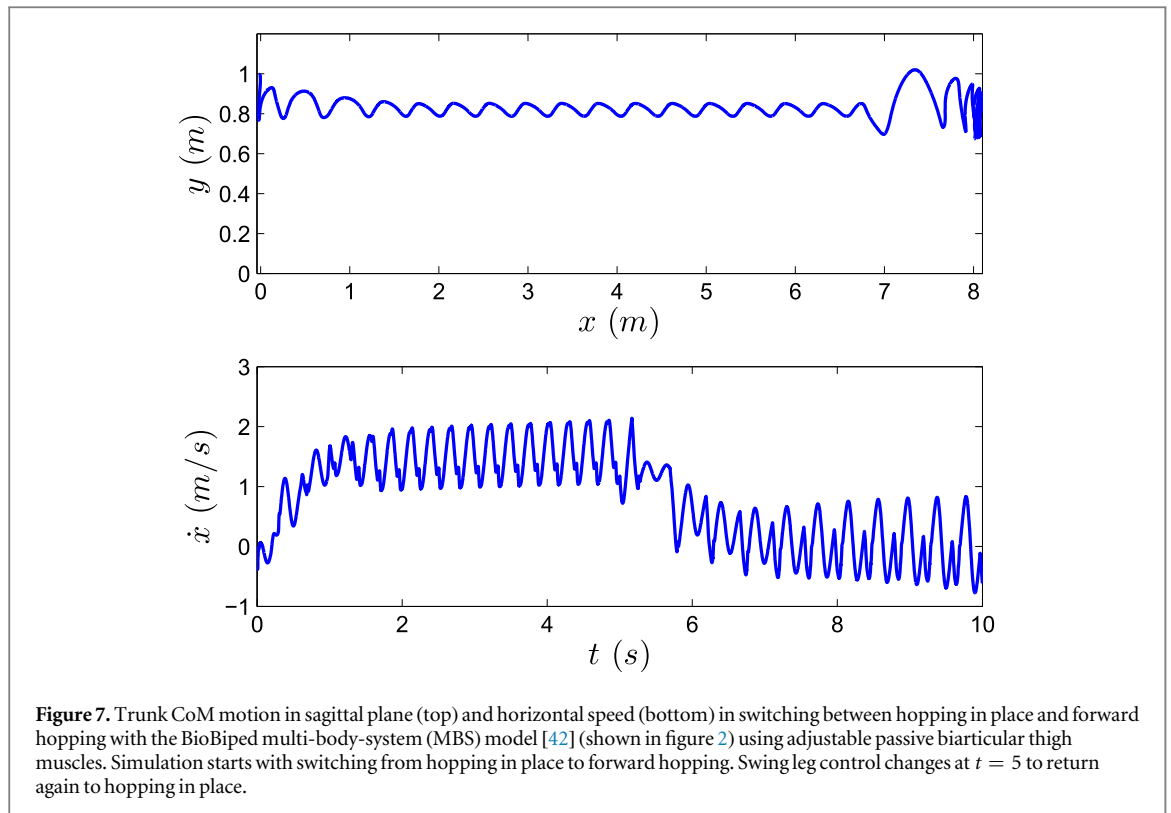


Table 3. Thigh biarticular muscle parameters (stiffness k and rest angle α) in forward hopping speed adjustment.

Parameter	Acceleration	Deceleration
α_{RF0}	90°	60°
α_{HAM0}	105°	100°
k_{RF}	12000 N m^{-1}	12000 N m^{-1}
k_{HAM}	12000 N m^{-1}	12000 N m^{-1}

higher. Figure 9 shows similar results for the squatting (dynamic) motion. Higher errors in control with monoarticular muscles and larger oscillations in GRF magnitude can be observed in this figure. The reason for larger oscillations in control with monoarticular muscles is its interference with knee actuator controller. However, the knee actuator is able to handle such effects which results in less than 2° differences between knee angles in two cases. The smaller the deviations from the desired GRF direction when using monoarticular muscles, the larger the errors in the kinematic behavior of the knee.

4.4. Passive rebound experiments with BioBiped3

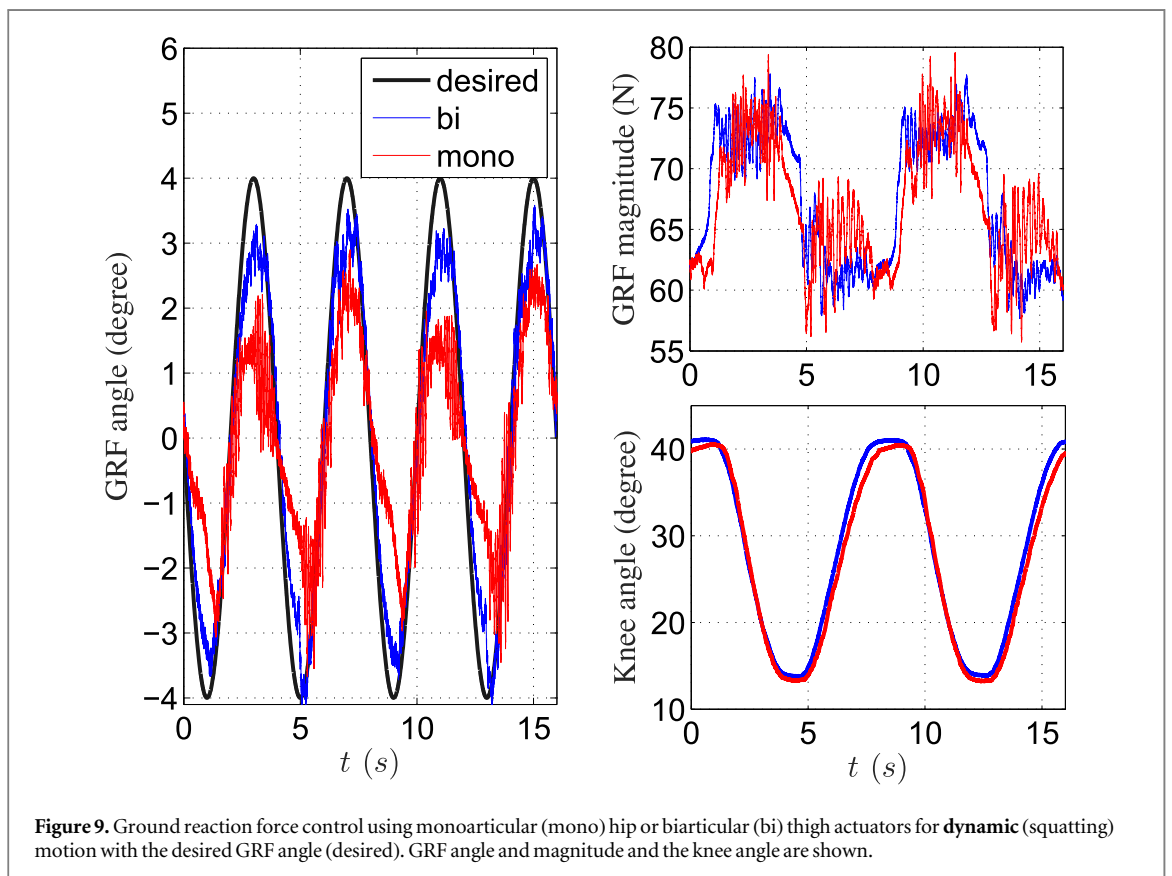
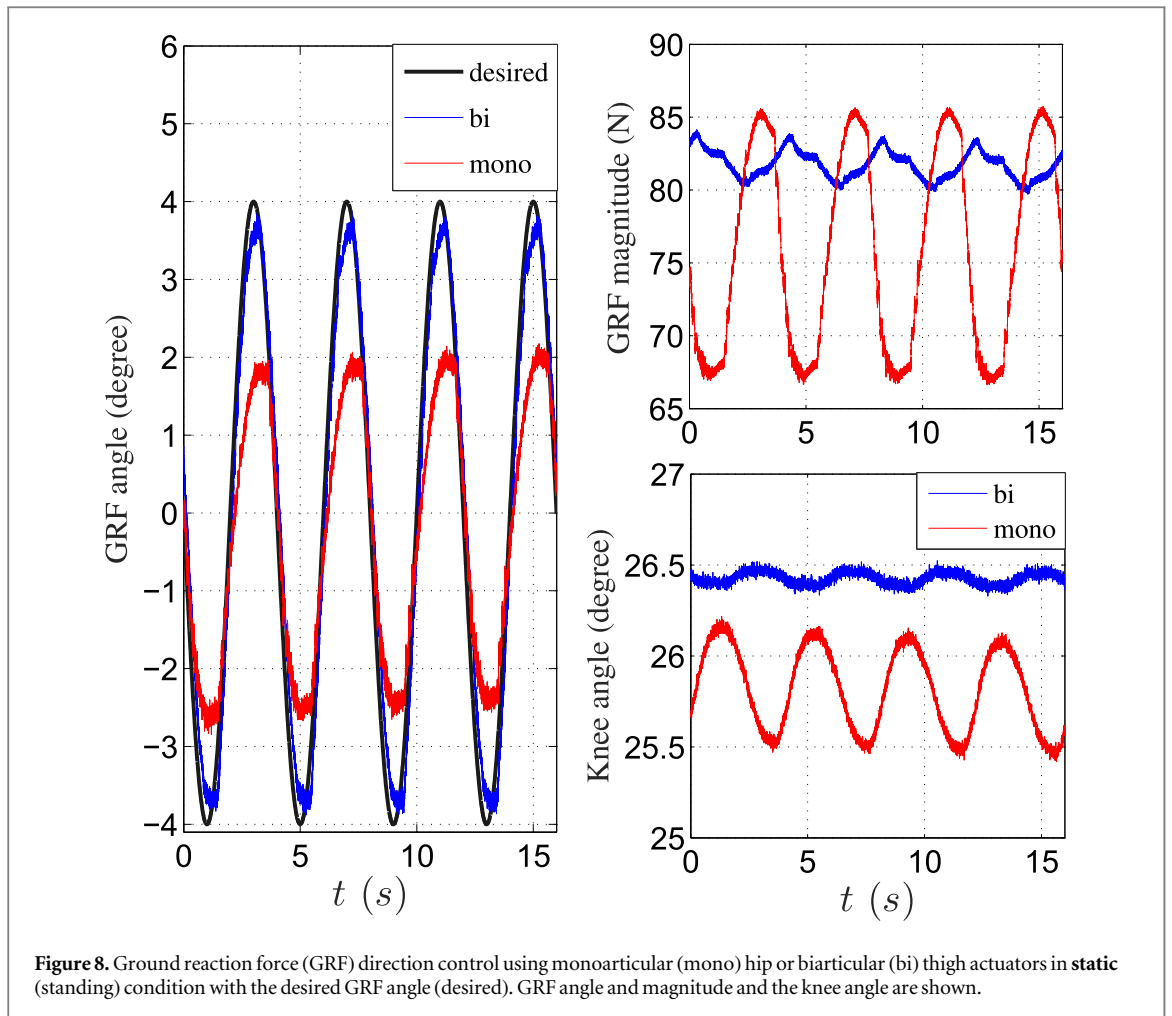
The passive rebound experiments show how biarticular actuators can support the axial leg function by synchronizing adjacent joints. Figure 10 shows the knee angle versus the ankle angle for one leg during the first rebound of the robot. A linear relation between these two angles means synchronized joints operation. In an extreme case, if the knee versus ankle joint angles' graph becomes a straight line, it signifies that

the two joints are completely synchronized and will move (extend/flex) together. With this definition, the knee and ankle joints are synchronized during falling for different GAS rest lengths, in contrast to rebound. The largest deviation from the linear relationship occurs when we remove GAS ($l_0^{GAS} = 0 \text{ cm}$) while the smallest deviation is achieved with ($l_0^{GAS} = -4 \text{ cm}$). This value also results in maximum rebounding height (2 cm) as shown in the attached video, while the largest variation corresponds to the lowest rebounding height. Synchronous joint operation is efficient as a positive (negative) joint work occurs in both joints at the same time. With this, internal energy losses by transferring positive work from one joint to negative work of the adjacent joint are avoided.

5. Discussions

A new biologically inspired biped robot was developed to investigate control concepts, extracted from simulations, human gaits studies and previous robot experiments. In addition to improving the robot hardware design using high quality sensors, motors and well suited feet, some modifications in actuation structure were considered.

The SEA design applied now to biarticular muscles enabled these actuators to work as passive springs with adjustable rest length (e.g., for swing leg control and improved energy management) or active compliant actuators for injecting energy (e.g., for postural control in the stance phase). Enhancement in leg control quality using biarticular actuators was demonstrated



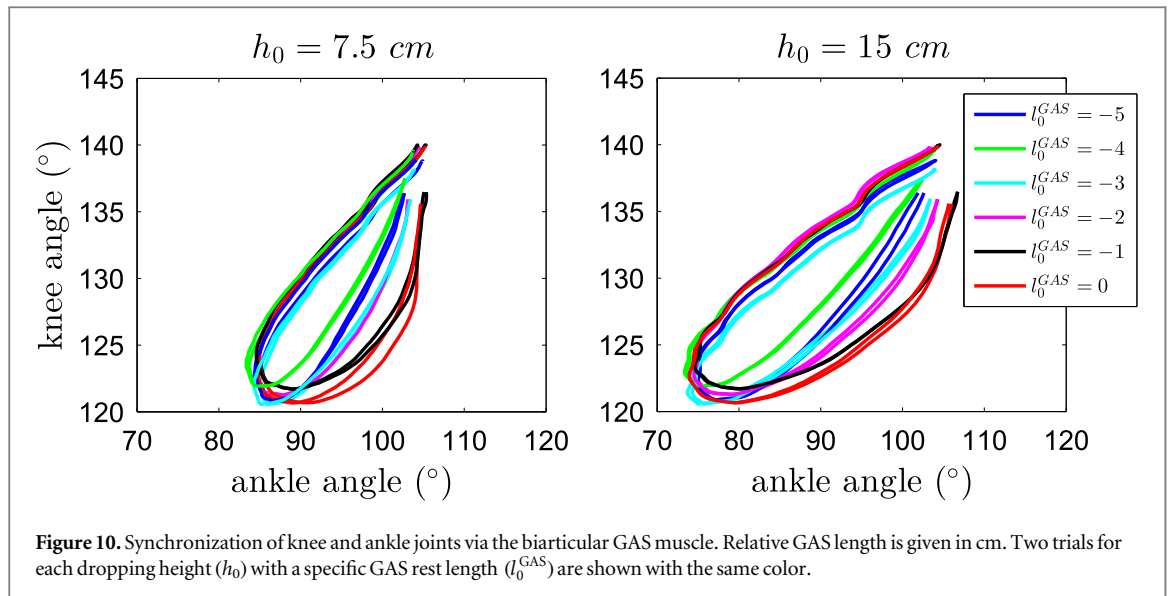


Figure 10. Synchronization of knee and ankle joints via the biarticular GAS muscle. Relative GAS length is given in cm. Two trials for each dropping height (h_0) with a specific GAS rest length (l_0^{GAS}) are shown with the same color.

by simulations and experiments of BioBiped3 robot. The multi-functionality of active biarticular structures can be exploited to facilitate control of locomotion sub-functions. Simplicity in control means simple controller rules (like PD or bang-bang control) and the minimum requirement of sensory information which are gained by aid of more complexity in mechanical design. For example, with the similar properties of SEA at hip monoarticular and thigh biarticular muscles, GRF control by monoarticular muscle is worse (larger errors and more oscillations) than that by biarticular muscle. To achieve similar performance, higher control effort and larger sensor and actuator bandwidth are required. These items can be used to assess simplification of control (e.g., with information-entropy-based approach presented in [43]) achieved by biarticular muscles.

Having biarticular actuators besides common monoarticular ones, provides several advantages which cannot be achieved by just two adjacent monoarticular actuators. Four of them which are demonstrated with experiments and simulations in this paper are: (1) direct access to perpendicular leg function with one actuator, (2) synchronizing adjacent joints without need for sensory feedback and high bandwidth actuator (3) passive energy transfer between adjacent joints 4) using motor redundancy (multiple actuators acting on one joint) to simplify control. In the following we discuss how these properties are achieved and how they can help improve locomotion control performance.

5.1. Posture control

The larger and the more consistent contribution (activation variations) of biarticular muscles (e.g., HAM) compared to monoarticular ones (e.g., GL) in perturbed standing experiments supports the idea of employing biarticular muscles for control of the perpendicular component of the GRF (section 4.1).

Therefore, providing access to balance control with small effects on axial leg function during the stance phase may help benefit from distribution of GRF control to different mono- or biarticular muscles. As a result, a simpler posture control strategy may be provided employing an appropriate mechanical design even with redundancy in actuators.

In order to validate this idea on our robotic setup (BioBiped3), GRF direction control experiments were performed in static and dynamic conditions (section 4.3). These experiments demonstrate that the cross-talk between control of GRF direction and axial leg function is lower in biarticular compared to monoarticular muscles. The larger influences of hip torque produced by monoarticular muscle on force in the axial direction (compared to biarticular muscle) behave like disturbances for knee motor position control and result in larger oscillations in GRF magnitude. In spite of some unmodeled dynamics in the real robot such as friction and inertia, the biarticular actuator can still decouple perpendicular from axial leg force. In both cases, static and dynamic, biarticular actuators perform better than monoarticular hip actuators in terms of GRF direction control. Especially in the dynamic case, GRF direction oscillates a lot when it is controlled with monoarticular hip actuators. This indicates that we can use biarticular actuators to facilitate balance control. Roughly speaking, the ability to focus the leg force in a desired direction allows for simple control strategies like VPP [36].

Compared to upright standing, during locomotion the joint torques might rely more on system and muscle dynamics (e.g. exploiting the intrinsic compliance of muscles) rather than on precise control of joint torques. Sudden perturbations could then be compensated by the action of biarticular muscles, which can instantaneously change perpendicular leg force as described above. Human walking experiments

support the suggested role of these muscles in tripping recovery [44].

5.2. Swing leg control

During the swing phase, biarticular actuators can support swing leg rotational movement control while monoarticular actuators (e.g., knee or ankle joints) can provide (axial) leg shortening and lengthening required for ground clearance. Such a task distribution can simplify control to setting spring rest lengths to a specific value for each gait condition (section 4.2). This simple control strategy which is able to produce human-like force and kinematic behavior in walking, was also implemented on BioBiped model for forward hopping. Setting the biarticular springs rest angles to new values for changing the motion speed provides the simplest swing leg control approach without needing sensory information of the joints (e.g., angles or angular velocities). Designing non-backdrivable actuators enables setting the springs' rest lengths to desired values and switching off the motors (no actuation) to have maximum efficiency during different phases of locomotion (e.g., swing phase).

In [41], the stance and swing leg movement contributions in human walking dynamics are analyzed. It is shown that their effects on the GRF are in-phase in the vertical direction, increasing the axial loading of the leg; in the horizontal direction, their effects nearly cancel. With the proposed DPS model with biarticular passive springs, similar contributions of swing leg in GRF can be obtained (figure 6). This further supports the idea of a far-reaching mechanical decoupling of an axial and a non-axial leg function. Therefore, using biarticular thigh springs not only results in stable and human-like swing leg movement, but also supports GRF control and balancing.

5.3. Energy management in stance

In addition to reducing energy consumption with the aid of biarticular muscles during the swing phase, such intelligent structures can support energy recoiling from one joint to another in the stance phase. If not perfectly tuned during stance phase of a bouncy task like jumping, adjacent joints (e.g., knee and ankle) act against each other or work out of phase. This results in inter-joint losses or asynchronous movements of joints which can be reduced using biarticular muscles [39, 40, 45]. With our passive rebound experiment (section 4.4), we could confirm that a passive biarticular muscle (GAS) with appropriate resting length can transfer energy from one joint to the other and improve jumping height instead of losing that energy by opposing actuations in adjacent joints. As shown in figure 10, for a specific motion condition, one rest angle for GAS muscle results in the most synchronized joints' movement and the highest energy recoiling. Therefore, an adjustable GAS in BioBiped3 enables us to select the optimal value for each gait. As a result, we

can benefit from geometry and physics instead of synchronization between two monoarticular actuators which needs precise measurements, actuators with large control effort, high bandwidth and detailed system knowledge.

Concluding, humanoid robots with bio-inspired design and control principles can demonstrate and evaluate biomechanical motion concepts and theories on legged locomotion. The versatile biarticular thigh muscles have the potential to simplify balance control in BioBiped3 during upright standing and locomotion. In addition, the GAS can be applied to improve the axial leg function in bouncing tasks (section 4.4) and was predicted to contribute to the catapult mechanism [46] in walking. In future, the novel anthropomorphic BioBiped3 robot can be used to demonstrate the enhanced motion capability regarding the locomotion sub-functions (repulsion, balance and swing leg motion) and in combining these features for achieving different gait patterns and gait conditions (e.g. speed and step length).

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