Hybrid Electric-Pneumatic Actuator (EPA) for Legged Locomotion
Project Proposal (Sachbeihilfe)

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1. State of the art and preliminary work

Legged robots comprise passive parts (e.g., segments, joints, and connections) which are moved in a coordinated manner by actuators. In this project, we will design a new hybrid actuator to outperform existing actuators in efficiency and robustness over the operational region required for human-like gaits. This section is organized as follows: **First**, we introduce and compare prevalent actuators used in legged robots (Table 1) and introduce ***electric-pneumatic actuator (EPA)***. **Second**, we provide a short summary of locomotion concepts which guide our search for the envisioned new actuator and why hopping is selected to demonstrate and evaluate locomotion control with the EPA. **Finally**, we present the preliminary results of an EPA setup and simulation model developed in our group recently.

Actuator literature review

Electric motors (EM) are widely utilized in legged robots (e.g., Asimo [1]). With these actuators either position control or torque control is achievable with high precision. Unfortunately, the EM's torque-velocity range with highest performance (e.g. power output) is not as wide as needed in legged locomotion. Furthermore, the impacts during locomotion may harm the actuator. In addition, weight/power ratios of EMs are not optimal for robots with a human-sized envelope.

Recently, **series elastic actuators (SEA,** [2]**)** became very popular in artificial legged systems [3, 4, 5]. Compared to EMs, in SEA with lower impedance, the impact resistance can be improved and the efficiency of the actuator can be increased by storing and returning elastic energy during the loading/unloading cycle (mimicking the stretch-shortening cycles in muscles, [6]). In contrast to SEAs which have a fixed stiffness, human muscles can adapt compliance and with that joint stiffness or leg stiffness to cope with changing ground conditions (e.g. damping, stiffness [7], rough terrain [8], recovering from perturbations [9]) and changing the motion speed [10]. To overcome this limitation of SEAs, stiffness adjustment was introduced in **variable impedance actuators (VIA)** [11]. VIAs are usually constructed by adding another EM (e.g. a direct drive servo motor) to the actuator design to control spring stiffness (e.g., via changing the lever arm or preloading of the spring) [12]. Even though this improves controllability of the output, the controller and the mechanical design are necessarily much more complex [11, 12]. In such designs, the second actuator usually has low power and low bandwidth, permitting a slow adjustment of the spring stiffness. Hence, the second EM is not designed to be employed as a power generator. Furthermore, both EMs are continuously consuming power during all movements - if they are backdrivable (e.g., as in the humanoid robot Veronica [12]), and hence are not energy efficient. Therefore, SEA (or VIAs with serial designs of EM and spring) can reduce the required power, but not the torque [13]. Recently, studies on considering parallel stiffness to the SEA (called SPEA) address this issue [13, 14]. Effects of parallel stiffness on reducing peak power and energy consumption of the actuator in prosthesis were described and compared with serial stiffness in [15, 16].

Hydraulic actuators (HA) are often used in larger legged robots (like PetMan [17], BigDog [18] or HyQ [19]) which require high torques. However, they are not so frequently used in research on legged systems due to their high price and low efficiency. In addition, the actuator properties (e.g., non-backdrivability and high impedance) are much different from biological actuators. For example, active impedance control [20] is needed to emulate the compliance that can be easily achieved with a passive spring in elastic actuators. Also, they can be dangerous when working in contact with humans. Because of these properties, hydraulic actuators are not used in this proposal.

Table 1. Comparison between different actuators for legged locomotion. Enhanced performance with EPA is expected. Preliminary experiments have been performed to support this idea which is explained later in this section. Colors show the preference. PAM: pneumatic artificial muscle, DDEM: direct drive electric motor, GEM: geared electric motor, SEA: series elastic actuator, HA: Hydraulic actuator and EPA: electric pneumatic actuator.

Properties	**PAM**	**DDEM**	**GEM**	**SEA**	**HA**	**EPA**
Bandwidth	low	high	high	low	high	high
Versatility in torque generation	medium	low	high	low	high	very high
Achievable range of motion	medium	high	high	medium	medium	very high
Achievable velocity	medium	high	medium	medium	high	high
Achievable torque	medium	medium	high	medium	very high	high
Efficiency	high	high	high	very high	very low	very high
Similarity to human actuators	high	very low	very low	medium	very low	very high
Robustness (impact resistance)	high	low	very low	high	high	high
Weight	very low	low	medium	medium	medium	low
Size	medium	low	medium	medium	medium	medium
Noise	high	very low	very low	very low	high	high
Price	very low	low	medium	medium	very high	low
User friendliness	very high	high	high	medium	medium	high
Intrinsic compliance	very high	very low	very low	very high	very low	very high
Backdrivability	high	very high	low	very high	very low	high
Position controllability	low	very high	very high	high	very high	high
directions of actuation	1	2	2	1	2	2

Pneumatic artificial muscles (PAM, [21, 22]**)** are (in part) similar to biological muscles [23]. They are compliant, cheap and lightweight, but they have low bandwidth (e.g., compared to EM and HA). Although most legged robots using PAMs are not precise in position or force control [24], they are efficient and have relatively simple controllers (e.g., bang-bang control for hopping) [25]. In addition, by tuning the compliance, PAMs can be used to reduce the energy consumption and also simplify control of complex humanoid robots [26].

Need for a new actuator. Muscles are arguably the best-known actuation technology that approaches a perfect force source i.e. one with extremely low impedance (perfectly back-drivable) and stiction, although with only moderate bandwidth [4]. Inspired by the functional performance and neuromechanical control of biological muscles [27], appropriate design of the actuator and control can largely enhance the locomotor function. If a robot without any passive compliance jumps or runs, even with precise force feedback control to have active compliance [19, 20], it has to cope with energy losses and compensate delay effects [25]. Adaptable compliances as found in biological systems provide significant advantages over traditional actuation for legged robots [28] and assistive devices (e.g., orthoses, prostheses) [29]. Although VIAs are rapidly developing with a wide range of different actuators, there is no “winning” design, but rather application-dependent optimal solutions [11].

Recently, a PAM-driven biped robot without any feedback was able to walk stably and to perform efficient hopping and running steps [25]. PAMs also provide adjustable compliance supporting periodic movements [26]. However, due to difficulties in force control and nonlinear air pressure-force behavior in PAMs, achieving stability based on analysis is often an issue in PAM-actuated legged systems. In these systems, stability is usually obtained by hand tuning of control parameters and is rarely investigated analytically. Combining the EM and PAM into an EPA may help improve controllability and overcome the drawbacks of each actuator type (e.g., increasing the bandwidth of PAMs by adding parallel EM in Macro-Mini scheme [30]). The combination of PAM and EM permits a variety of arrangements, (see Sec. 2.3.2). For example, using PAM instead of springs in a SEA, allows us to adjust the compliance as in VIAs. This makes the system more efficient (compared to EM) and more robust against impacts. The addition of a parallel PAM to this design (as adjustable passive compliance) can also reduce EM torque when not all of the torque does pass through the motor. Studies on parallel stiffness show that this resolves a main drawback of compliant actuators with series compliance [13, 16]. Furthermore, with this new combination, we can also benefit from muscle-like properties of lightweight PAMs [23], e.g., using compliance control techniques [26]. As different (biological) muscles may have different functions during a specific task (e.g. operating as spring, drives or brakes), this can be represented by a muscle-specific design of EPA, as combinations of PAM and EM (e.g., with series, parallel, antagonistic arrangements). In Table 1, different types of actuators have been compared in terms of their suitability for legged locomotion. The expected performance of an optimally designed and controlled EPA (last column of Table 1), is greater than of contemporary actuators. Preliminary results presented in the following confirm this claim.

Locomotion control and hopping as a primitive locomotion task

Legged locomotion can be composed of three locomotor sub-functions [31]: **Bouncing** (axial leg function), **leg swinging** and **balancing,** (Fig.1). **Bouncing** describes the elastic rebounding of the stance leg (ground contact) to counteract gravity [32]. **Leg swinging** is mainly a rotational movement of the swing leg [33] combined with a minor axial leg movement for ground clearance. Since a major part of the body mass is located on the upper body, the human body is inherently unstable [34] and **balancing** (posture control [35], [36]) is considered to be a third locomotor sub-function, as a key feature of human walking. There are studies on combinations of the control concepts of three locomotor sub-functions to achieve stable gaits [37, 38, 39, 40]. Based on them, an actuator can be designed with optimal performance for a range of motions required for different locomotor sub-functions.

Template models [41] - despite their high level of abstraction - are very useful tools to understand how these sub-functions are controlled and coordinated, both in nature [32] and legged robots [42]. In this proposal, we focus on bouncing as the first locomotor sub-function and how the new actuator can be advantageous for bouncing. EPA for the next two sub-functions will be implemented and evaluated in a follow-up project. A spring-loaded inverted pendulum (SLIP) model [32] is a simple template model describing human-like axial leg function in walking and running [43]. Extended SLIP models, like ESLIP [44] or the variable leg spring (VLS) model [45], describe leg spring adjustments (stiffness, rest length) during the stance phase. They provide better representations of human bouncing behavior, which can be used for control of a real system and can be easily implemented by EPAs. Hopping can be considered as a prerequisite movement for running. In the SLIP model, there is no difference between forward hopping and running, as there is no actuation required for swing leg adjustment (massless leg) [46]. In addition, hopping is the only gait that is feasible just with one leg.

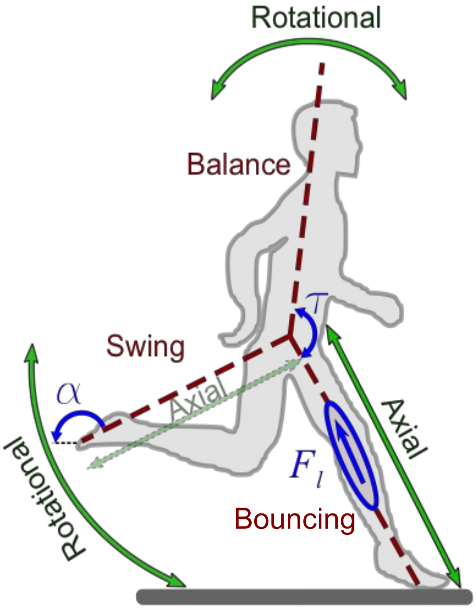


Figure 1. Main contributions of bipedal locomotor sub-functions: **bouncing** (repulsive axial leg function), **balancing** (postural control) and **leg swinging** (rotational swing leg movement, besides minor axial leg function).

Interestingly, it was found that the combination of locomotor sub-functions based on implicit coordination (with a limited exchange of sensory information) can produce stable forward hopping [37, 40]. Thus, hopping can be considered as the simplest gait for evaluating optimal EPA design regarding the orchestrated control of locomotor sub-functions (i.e., enabling a harmonized operation of the underlying sub-functions). In this first phase of the EPA project, we aim at design and develop an optimal EPA and implement it on our existing hopping systems. In our lab, we have worked on a series of hopping robots [5, 45]. In the 1D MARCO-Hopper [47], different energy management approaches for robust hopping with varying ground level were studied and compared to human experiments. In the MARCO-2, this approach was extended to a two-segment leg and a modular actuator unit (with SEA). This setup enables the comparison of different actuator designs for realizing bio-inspired hopping movements. Simulation and experimental results show a successful transfer of SLIP-based control approaches from MARCO [48] to MARCO-2 [49, 50]. Similar results were observed in a simulation model of the BioBiped robot [39]. These concepts were extended to 2D movement resulting in stable and easily adaptable forward hopping gaits [38]. We envision extending this approach in a follow-up project to address further one/two-leg gaits.

Biomechanical studies on human movement show that walking and running can be formulated as optimal control problems [51,52]. In humanoid robots control, the optimal control is also used to generate walking motions [53], using forward control for dynamic modeling and objective function formulation. However, in biomechanics approximating the human/animal objective function is also very important to understand the biological behavior. Formulating biological locomotor movement as an optimal control problem is addressed in ***"inverse optimal control"*** method [51-54]. This technique consists of two steps: (i) parameter identification for cost function estimation and (ii) the optimal control problem [51-54]. In this proposal, we aim at using the inverse optimal control to identify the cost function, which should be optimized to reach the properties of the human actuators (muscles) in hopping. Then, this cost function will be adapted to be used in defining optimal actuator.

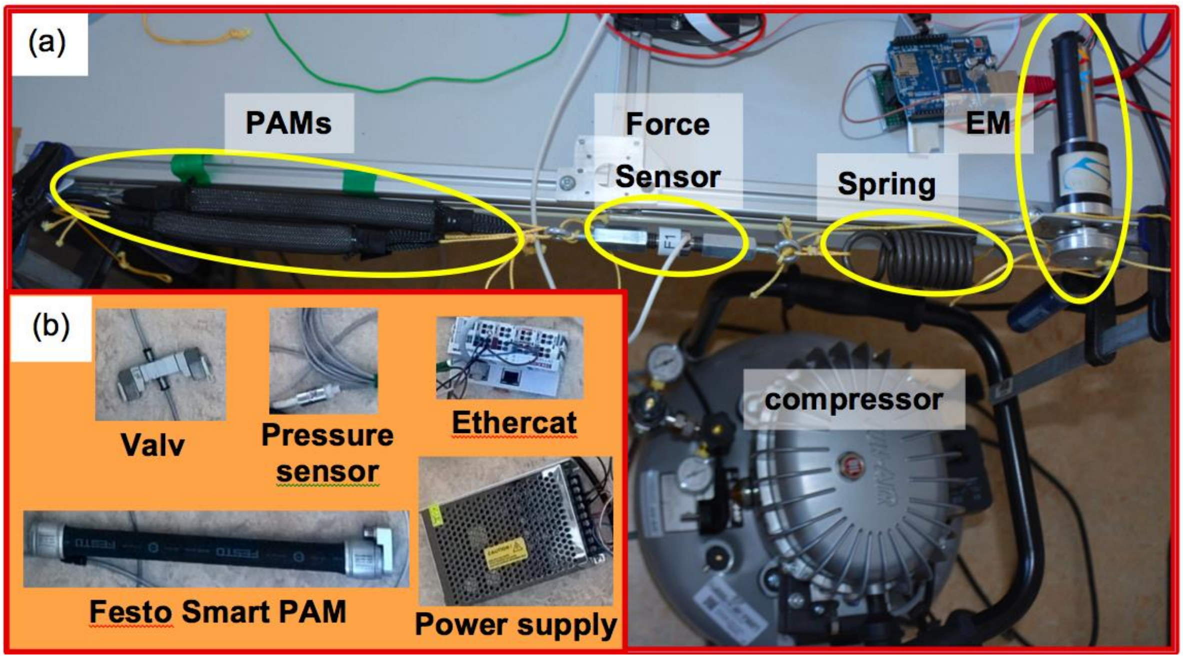


Figure 2. (a) Preliminary version of EPA-Testbed with the serial arrangement and additional spring to identify a dynamical model of PAM (b) Different other elements employed in the experiments.

Preliminary results of developing EPA setup and model

In collaboration with HOSODA lab in Japan, we have developed an elementary model and a preliminary hardware setup of EPA (EPA-Testbed) to demonstrate the advantages of the new hybrid actuator (Fig. 2). As mentioned before, locomotion can be developed by a combination of oscillatory movements for different locomotor sub-functions. For any active oscillating mechanism (e.g. actuated spring-mass system), there exists a natural frequency, which needs the minimum effort to move. By modeling a joint instrumented by an SEA, it is shown that for a periodic movement (mimicking bouncing in locomotion), one optimal stiffness exists for each frequency. By adjusting the spring stiffness to this optimal value, the actuator can move the systems states from any initial condition to the desired limit cycle and just compensate losses afterward. In the ideal case (without losses), the motor may rest after reaching the limit cycle. With SEA it is not possible to change the stiffness. However, in EPA (Fig. 2a), PAM air pressure can be used to adjust stiffness. Using the existing static models of PAM, we developed an EPA simulation model with serial configuration and showed how fine-tuning of PAM results in an efficient control by EM. In bouncing the optimal muscle stiffness for different hopping conditions (e.g., frequency) can be identified with this approach. Note that the additional energy for adjusting the PAM (compared to SEA) is required just once for each hopping condition and after reaching the limit cycle, PAM does not spend any extra energy with closing the valves. Still, the control complexity of the EPA is similar to that of an SEA.

In our developed setup (shown in Fig 2), the actuator is instrumented by a force sensor, a pressure sensor, and an encoder. Using the compressor, 2Hz valves, and the pressure sensor we adjust the muscle pressure. By moving the EM with different frequencies, we identify the dynamic model of the PAM. The developed model will later be used in the simulation model for designing and controlling the actuator.

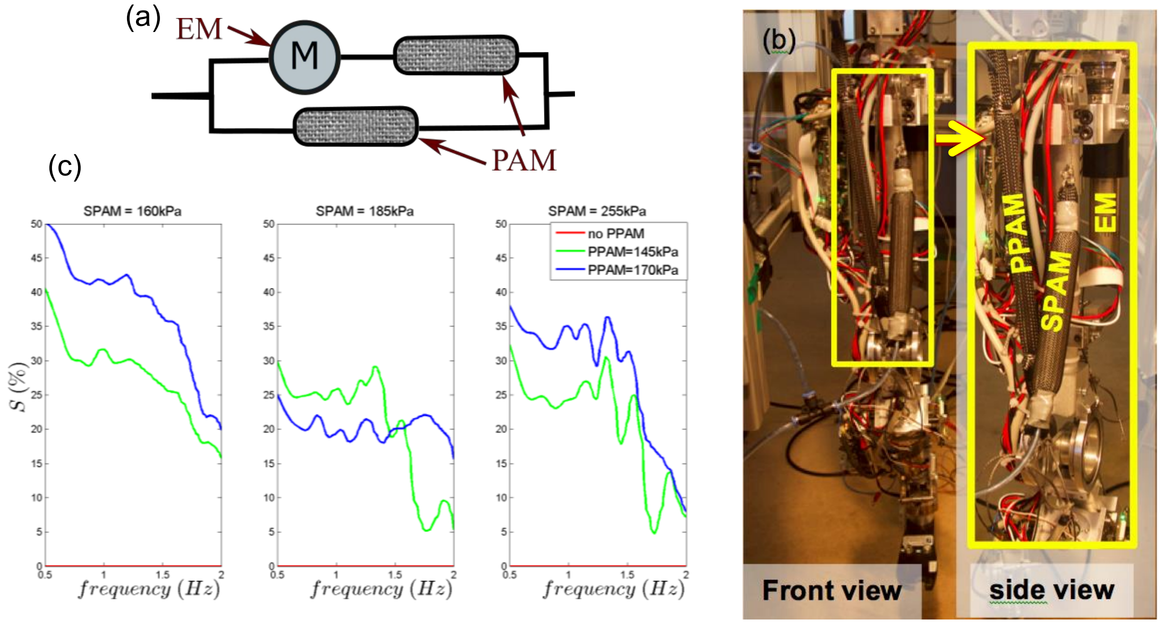


Figure 3. Integration of PAM in BioBiped3. (a) Schematics of PAM arrangement. (b) Implementation of EPA in BioBiped3 representing the Vastus muscle, including one electric motor (EM), one serial (SPAM) and one parallel PAM (PPAM). The knee joint angle is PID controlled. The desired joint position is a sinusoidal wave with frequency linearly increasing from 0.5Hz to 2Hz (over a period of 5 minutes). (c) The approximation of saved energy (S) compared to no PPAM case is shown for different PAM pressures and oscillations frequencies. The atmosphere pressure is about 100kPa.

We have also arranged a preliminary experiment using the BioBiped3 robot (Fig. 3a). In this experiment, we fixed the robot trunk and employed the knee actuator to generate a periodic movement at different frequencies. The SEA for the Vastus muscle is replaced by an EPA in which two PAMs are applied in series (SPAM) and in parallel (PPAM) to the actuator (Fig. 3a,b). The desired joint position is given by a sinusoidal signal, in which the frequency is increasing linearly from 0.5Hz to 2Hz in 5 minutes. The effects of SPAM and PPAM pressures on energy consumption at different frequencies are shown in Fig.3c. The integrated current square ($E = \int_T I^2 dt$) is used as a measure of energy. Saved energy $S = (E_P - E_0)/E_0$ is shown in percent to compare the results with different PPAM pressures, while $E_0$is no PPAM and E_P is with PPAM having pressure P. For a fixed SPAM, the consumed energy is the maximum for no PPAM arrangement. Conclusively, adding PPAM reduces energy consumption. In addition, comparing nonzero pressures for PPAM shows that for a specific SPAM, the frequency determines which stiffness (respectively pressure) reduces energy consumption. For example, when SPAM=185kP, for frequencies below 1.5Hz, S for PPAM=145kPa is more than that of PPAM=170kPa, whereas for frequencies above 1.5Hz, PPAM=145kPa is more efficient. Similar argumentations are valid for SPAM. Therefore, to move with a certain frequency, stiffness adjustment of the PAMs can result in reduction of energy consumption and peak power.

1.1. List of Project-related publications

1.1.1. Articles published by outlets with scientific quality assurance, book publications, and work accepted for publication but not yet published.

Maziar Ahmad Sharbafi, Christian Rode, Stefan Kurowski, Dorian Scholz, Rico Möckel, Katayon Radkhah, Guoping Zhao, Aida Mohammadinejad Rashty, Oskar von Stryk and Andre Seyfarth, “A new biarticular actuator design facilitates control of leg function in BioBiped3”, *Bioinspiration & Biomimetics*, vol. 11, no. 4, 2016.

M. A. Sharbafi, C. Maufroy, M. Nili, M. J. Yazdanpanah, and A. Seyfarth, “Robust hopping based on virtual pendulum posture control”, *Bioinspiration & Biomimetics*, vol. 8, no. 3, 2013.

M. A. Sharbafi and A Seyfarth, “Stable running by leg force modulated hip stiffness”, in *IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob),* 2014.

M. A. Sharbafi, K. Radkhah, O. Von Stryk, A Seyfarth, “Hopping control for the musculoskeletal bipedal robot: BioBiped”, in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2014.

M. A. Sharbafi and A Seyfarth, “FMCH: a new model for human-like postural control in walking”, in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),* 2015.

J. Oehlke, **M.A. Sharbafi**, P. Beckerle, and A. Seyfarth, “Template-based hopping control of a bio-inspired segmented robotic leg”, In 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp. 35-40, 2016.

M. Grimmer, M. Eslamy, S. Gliech and **A. Seyfarth**, “A Comparison of Parallel and Series Elastic Elements in an actuator for Mimicking Human Ankle Joint in Walking and Running,” in *IEEE International Conference on Robotics and Automation (ICRA)*, 2012.

A. Seyfarth, S. Grimmer, H.-M. M. D. Haeufle, F. Peuker, and K.-T. Kalveram, "Biomechanical and Neuromechanical Concepts for Legged Locomotion", in *Routledge Handbook of Motor Control and Motor Learning*, Routledge, pp. 90-112, 2013.

H. Geyer., **A. Seyfarth**, & R. Blickhan, “Compliant leg behaviour explains basic dynamics of walking and running” in *Proceedings of the Royal Society of London B: Biological Sciences*, vol. 273, no. 1603, pp. 2861-2867, 2006.

D. F. Haeufle, S. Grimmer, K-T Kalveram and **A. Seyfarth**, “Integration of intrinsic muscle properties, feed-forward and feedback signals for generating and stabilizing hopping”, in *Journal of The Royal Society Interface*, vol. 9, pp. 1458-1469, 2012.

1.1.2. Other publications

1.1.3. Patents

1.1.3.1. Pending (N/A)

1.1.3.2. Issued

H. Geyer, H. Herr & A. Seyfarth, U.S. Patent No. 7,295,892. Washington, DC: U.S. Patent and Trademark Office, 2007.

2. Objectives and work program

2.1. Anticipated total duration of the project

The envisioned duration of the project is 6 years which is split to two 3-years sub-phases. In this proposal, we focus on and apply for the first phase (from March 2017 until February 2020) while the general objectives are valid for the whole project.

2.2. Objectives

Compared to muscles (as biological actuators), a similarly appropriate actuator for legged robots is still missing. This actuator needs to be energy-efficient and robust against perturbations (e.g., impacts) over a range of different gaits and conditions (e.g., speed). In this project, we aim at designing such an actuator by combining the advantages of electric motors (EM) and pneumatic artificial muscles (PAM). We call this novel electric-pneumatic actuator EPA, which is easily adjustable for different locomotor conditions. In the following, we will explain how the EPA design can be used to implement basic locomotor sub-functions.

Motivation: In the biological body, different muscles have similar general functionality but vary in contraction properties (e.g., maximum contraction speed, maximum isometric force). In robotics, we may replicate this by different actuator types (e.g., electric motors, pneumatic & hydraulic actuators). Electric motors are well suited for continuous operation with constant speeds. In contrast, pneumatic actuators are well-suited to mimic compliant behavior, but they fail in accurate control (e.g., position control). As both of them individually cannot well replicate biological actuation, we propose combining them to better match the requirements for legged locomotion.

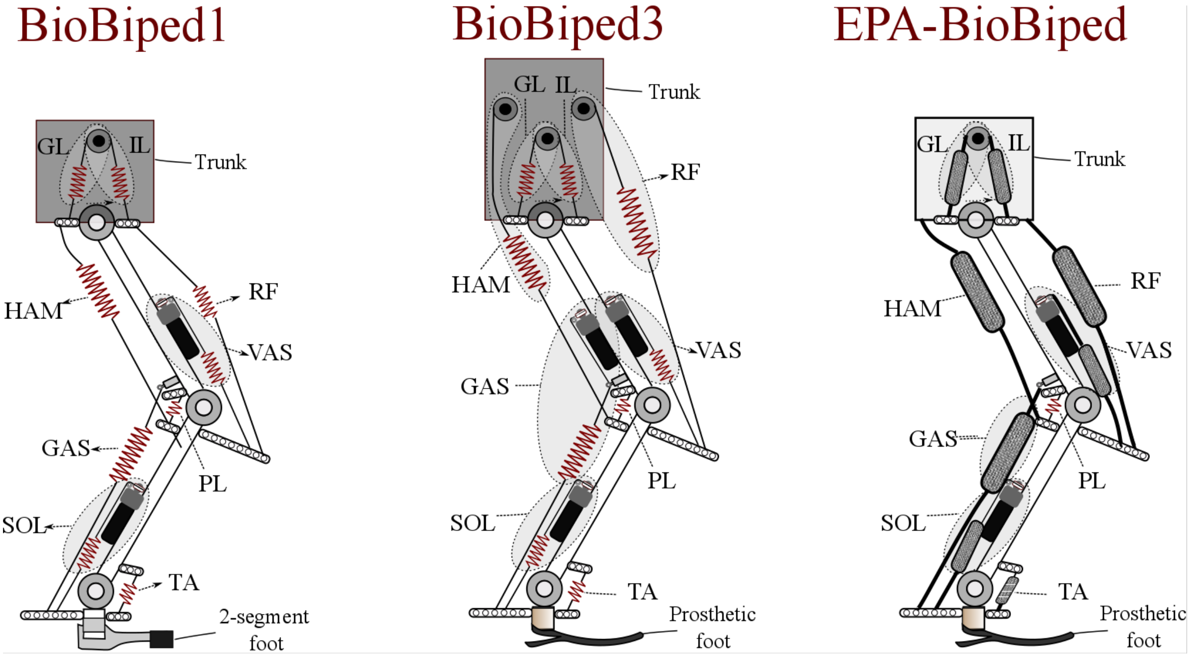


Figure 4. Left two panels: BioBiped 1 and 3 robot series. Right panel: the concept for an EPA-instrumented BioBiped by replacing SEAs with EPAs and passive springs with PAMs.

In the DFG project BioBiped (www.biobiped.de), which was accomplished by Lauflabor and SIM group (TU Darmstadt), series of robots were designed and developed to mimic human leg structure (representing 9 muscle groups with springs and SEAs) for locomotion (Fig. 4 left and middle panels). A main limitation of the BioBiped robot was the missing ability to adjust the SEA spring stiffness [64] representing the function of leg muscles. With EPA, we can easily adjust the stiffness using lightweight PAMs which can be employed as either actuator or adjustable compliance. In Fig. 4, an example of EPA instrumented BioBiped (called EPA-BioBiped) is suggested. Such a design introduces a more human-like muscle-skeletal structure for mimicking human gaits. Although this is not the goal of this proposal, the EPA-

BioBiped concept motivates the development of the novel biologically inspired hybrid actuator.

Approach: In locomotion, actuators contribute to different locomotor sub-functions like bouncing (elastic axial leg function), balancing and leg swinging. These three sub-functions of the human leg result in different actuator and control requirements as explained in Table. 2. To realize the above-defined locomotor sub-functions, we aim at designing function-specific EPA setups (i.e. specific configurations of electric and pneumatic actuators with corresponding control schemes). In this proposal, we concentrate on the first sub-function, bouncing that can generate hopping in place. The other two sub-functions are not the focus of this proposal remain for a subsequent research. We envision the following steps to implement and assess the capacity of the EPA design and control for realizing efficient and robust dynamic motions:

1. **Modeling:** We prepare EPA actuation models to test different arrangements of electric and pneumatic actuators regarding their performance for locomotor sub-functions. We have built preliminary models in MATLAB, in collaboration with Hosoda lab in Japan. We will develop a musculoskeletal model of hopping in OpenSim to identify human muscle cost functions in hopping.
2. **Human experiments:** Based on unperturbed and perturbed hopping data, optimization criteria (cost function) for EPA design and control will be derived regarding efficiency, robustness and versatility. We use inverse optimal control to find the cost functions, (see, Sec. 1).
3. **Hardware testbeds:** EPA will be tested in an actuator performance testbed (**EPA-Testbed**, similar to Fig. 2) to tune the EPA model. MARCO-2 (vertical hopping robot with segmented leg, Fig. 5) will be equipped with EPA (**EPA-Hopper**) to evaluate resulting hopping performance.
4. **Hardware experiments:** Based on the hopping performance we will identify optimal EPA designs with matching control strategies (inspired from human hopping and template models) in comparison to SEA and direct drive.

Table 2. Overview of locomotor sub-functions with basic characteristics and their representation in template models. The leg axis is defined as the connecting line between hip and ankle joint (Fig.1).

locomotor sub-function	**objective**	**force direction**	**representation in biomechanical template models**
bouncing	bouncing like a pogo stick	in leg axis	leg spring (axial)
leg swing	adjust leg orientation during the swing phase	perpendicular to and in leg axis	leg + hip spring (axial + rotational)
balance	maintaining an upright body orientation	perpendicular to leg axis	hip spring (rotational)

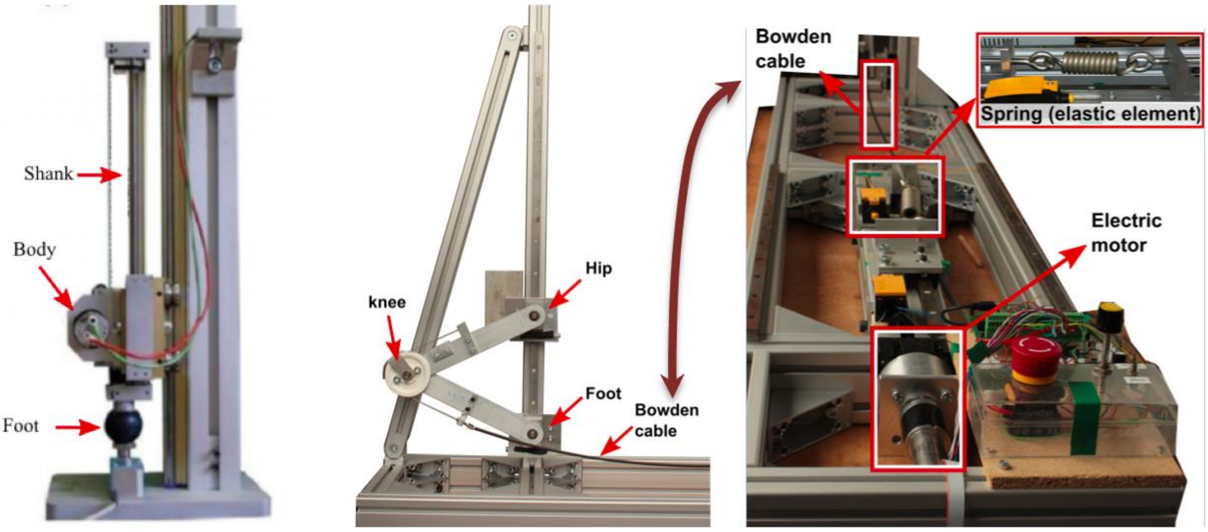
Control of EPA:

In comparison to serial/parallel elastic actuator (S/PEA), control of EPA requires two new features resulted from added functionality of PAMs:

- ✓ tuning of compliance (maintain constant PAM pressure)
- ✓ injection/withdrawal of energy (sudden change PAM pressure)

The PAM combines a simple mechanism for adjustable compliance with a powerful, low weight, low cost, and robust actuator. It permits fast energy injection (high power density related to actuator mass) and operates without a gear (because it provides high power at low speed) in similar conditions as required for legged locomotion (e.g. regarding speed, force and impact resistance). For a periodic movement of the actuators during steady state gaits, compared to SEAs we expect to find EPA design and control, which can reduce energy consumption while keeping robustness against perturbation. For example, tuning the natural frequency by PAM can result in a very efficient hopping using EPA, (similar to control of joint position through EM similar to BioBiped experiment, see Sec. 1).

Compliant actuators support the ability to mimic movements close to those predicted by gait template models. In the SLIP model, the repulsive axial leg function is described by the concept of a leg spring, which can be directly employed to control the actuators. To match experimental data in human walking and running, the leg spring parameters (leg stiffness, rest length) need to be adaptable during stance phase ([56]). This is in line with conceptual models of bipedal locomotion. SLIP-based models can describe human locomotion more realistically when changes in leg stiffness and rest length are taken into account [44, 45]. In [47-50], we have employed an electric motor to emulate spring-like behavior of the leg with a variable stiffness for energy management (e.g., with bang-bang or linear increasing approach). With EPA, stiffness and rest lengths can be easily changed by adjusting PAM pressure and EM position, respectively. With this combination we expect to achieve asymptotically stable limit cycle with simple controllers. Furthermore, the energy efficiency and robustness could be improved. Such a variable impedance actuator could have additional advantages in **leg swinging** and **posture balance** control, which are not addressed in this project.



(a) (b) (c)

Figure 5. (a) MARCO-Hopper with prismatic leg, (b) MARCO-2 with segmented leg and (c)separate modular actuation mechanism, connected by Bowden cable. In this project, MARCO-2 will be equipped with EPA actuators resulting in the EPA-Hopper (not shown).

Expected outcome

In summary, we expect that integrating PAMs and EMs in a hybrid EPA provides the following advantages for locomotor systems:

- ✓ EPA behaves like SEA with tunable stiffness (by adjusting pressure and closing valves)
- ✓ simple control, combining adjustable compliance (from PAM) and precise position or force control (from EM)
- ✓ large range of energy efficient actuator function (as the pneumatic actuator can be used as an adjustable spring). The PAM can be used as an actuator, which operates efficiently at low speeds and high forces, while electric motors operate efficiently at high speeds/frequencies [30].
- ✓ robustness against impacts and other mechanical perturbations (due to PAM compliance)
- ✓ ability to allocate different duties to either electric or/and pneumatic actuators in performing a specific locomotor sub-function (here, bouncing).

2.3. Work program

2.3.1. General organization of the research

We develop the EPA as a variable impedance actuator (VIA) in the following way: First, we search for an *optimal design* of the actuator. This means finding the EPA structure to make the best tradeoff between the **energy efficiency** and **robustness against perturbations** (e.g., unexpected forces) in a large range of actuator dynamics required for **versatile locomotion**. In order to define a biologically inspired measure for *optimality*, we do human hopping experiments (with ground level perturbations) to search for an appropriate **trade-off between efficiency, robustness and versatility.** By developing a simulation model of this experiment, we apply inverse optimal control to approximate the cost function, which should be minimized to achieve the human muscle properties. To find the *optimal actuator* representing a muscle, we examine different arrangements of pneumatic and electric actuators (serial, parallel, antagonistic) in simulation, searching for the one which can minimize the human-inspired cost function. We need a simple EPA setup to control a joint (**EPA-Testbed,** as explained in preliminary results of Sec. 1). With that we can evaluate the basics on actuator control and also predict improvements on a hardware system. Then, the applicability of the proposed approaches on a real locomotor system will be tested on **EPA-Hopper** and the results will be compared with other types of actuators (direct drive and SEA). Similar to our previous works on Marco-2 [50, 55], we investigate bio-inspired (SLIP-based) controller for hopping. We expect to achieve lower costs with optimal EPA properties, using this controller on the EPA-Hopper.

Description of the robotic setups

EPA-Testbed: We have designed and manufactured a preliminary EPA setup (Fig. 2) to learn about the actuator properties and identify the dynamic model. We plan to complete the existing setup for identification and first round experiments of evaluating different arrangements of EPA in control.

EPA-Hopper. The target experiment with EPA-Hopper is stable 1D hopping based on the SLIP model concept and evaluating its efficiency, robustness against perturbation and ability to change hopping height and frequency with the minimum control effort.

This project is divided into three work packages, which are described below. Table 3 shows the work distribution including the members contributions.

Table 3. Gantt chart with the contribution of project members associated to tasks and work packages.

<table>
<tr><th>WPs</th><th>Positions</th><th colspan="2">M1-M6</th><th colspan="2">M7-M12</th><th colspan="2">M13-M18</th><th colspan="2">M19-M24</th><th colspan="2">M25-M30</th><th colspan="2">M31-M36</th></tr>
<tr><td rowspan="3">WP 1</td><td>PostDoc</td><td>T1.1</td><td colspan="2">T1.2</td><td>T1.3</td><td>T1.4</td><td colspan="7" rowspan="3"></td></tr>
<tr><td>PhD</td><td>T1.1</td><td colspan="2">T1.2</td><td>T1.3</td><td>T1.4</td></tr>
<tr><td>Stud Res</td><td>T1.1</td><td>-</td><td colspan="2">-</td><td>-</td></tr>
<tr><td rowspan="3">WP 2</td><td>PostDoc</td><td colspan="2" rowspan="3"></td><td>-</td><td colspan="2">T2.2</td><td>T2.3</td><td colspan="2">T2.4</td><td colspan="4" rowspan="3"></td></tr>
<tr><td>PhD</td><td>T2.1</td><td colspan="2">T2.2</td><td>T2.3</td><td colspan="2">T2.4</td></tr>
<tr><td>Stud Res</td><td>T2.1</td><td colspan="2">T2.2</td><td>-</td><td colspan="2">-</td></tr>
<tr><td rowspan="3">WP 3</td><td>PostDoc</td><td colspan="7" rowspan="3"></td><td>T3.1</td><td colspan="2">T3.2</td><td>T3.3</td><td>T3.4</td></tr>
<tr><td>PhD</td><td>T3.1</td><td colspan="2">T3.2</td><td>T3.3</td><td>T3.4</td></tr>
<tr><td>Stud Res</td><td>T3.1</td><td colspan="2">-</td><td>-</td><td>-</td></tr>
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2.3.2. Description of the Work Packages

2.3.2.1. Work Package 1: Actuator design criterion

Hypothesis: *Optimal actuator design criterion for hopping can be derived from human data.*

WP1	**Actuator design criterion (M1-M15)**
Purpose	Deriving quantifiable cost function for actuator performance in human hopping.
Tasks	**T1.1 (M1-M3)** Experiments on human hopping (with different hopping heights and frequencies) on the perturbation platform (Fig. 6). We will examine at

	least 15 subjects with and without ground level perturbations.
	T1.2 (M4-M9) Data analysis, including kinematics, kinetics, muscle activation and muscle forces using openSim (http://opensim.stanford.edu/)
	T1.3 (M10-M12) Identifying relation between energy efficiency and robustness against perturbations under different hopping conditions (e.g., speed or frequency).
	T1.4 (M13-M15) Providing a measure (optimization cost function) for optimal EPA design using outcomes of T1.3. Inverse optimal control is employed to find the cost function from the estimated human muscle performance (T1.2).
Milestones	**M1.1** Providing a complete data set of perturbed/unperturbed hopping including kinetics, kinematics muscle activation and estimated muscle force.
	M1.2 Providing an open source neuromuscular model of hopping.
	M1.3 A bioinspired actuator design criterion for locomotion (here, hopping).
	M1.4 A new actuator design method based on human motor performance.

In this WP we prepare the infrastructure to develop and demonstrate the human-inspired actuator and control strategies for the bouncing sub-function, later used in WP2 and WP3.

We **perform human experiments** to find a measure (cost function for optimization) for compromising between robustness, efficiency, and versatility in humans' locomotion. In order to achieve this goal, we consider selected leg muscles and study their contributions to the axial leg function. This will allow us to estimate the required actuator properties of individual muscles in the simulation. In WP2, we apply the developed cost function to find the optimal actuator for specific tasks. The sequence of tasks in this WP can be summarized as follows:

T1.1 (all): In this task, a hopping experiment is performed. The subjects (about 15) are asked to hop on the perturbation platform for about one minute. Different hopping frequencies and hopping heights are examined to cover the region of human hopping. In some randomly selected "perturbation trials", the ground level is moved up or down. These perturbations may happen during stance phase or flight phase. We measure the kinematics (Qualisys high-speed motion capture system), kinetic (Kistler force plate mounted on perturbation platform) and EMG signals (Delsys). In this task, the students prepare the setup and the subjects for experiment with support of the the PhD and the PostDoc is responsible for the organization and execution of the experiments. More details about the experiments are explained in the ethical documents.

T1.2 (PhD & PostDoc): This task includes data processing, data analysis, and neuromuscular modeling. Data processing and analysis (M4 to M6) comprises joint marker tracking, identifying invalid data, ground contact detection, calculation of center of pressure (CoP) using ground reaction forces (GRF), CoM approximation using kinetic and kinematic data [59], rectification and filtering the EMG signals, synchronizing data of different measurement systems, data labeling (e.g. subjects, trials). The processed data are stored such to be readable in MATLAB and OpenSim. Joint torques are calculated based on inverse dynamics in MATLAB. We apply the data to the OpenSim model of hopping. We use this model to approximate muscle forces for unperturbed and perturbed hopping. In the cost function that we use for approximating muscle forces we include kinetic, kinematic and EMG signals to minimize the error between the data and the model.

T1.3 (PostDoc & PhD): Knowing the motion dynamics, muscle forces and perturbations, we can analyze muscle force generation and their response to perturbations. In this task, the goal is finding relations between different muscle forces and the desired movement (with respect to hopping conditions e.g., frequency or height) and also their responses after perturbations. Therefore, we have two steps: i) **Efficiency in steady state**: In unperturbed hopping, we analyze the muscle dynamics and the whole body movement dynamics. We search for adaptation of the muscle activation patterns to the hopping frequency, muscle developed forces w.r.t ground reaction force and muscle power w.r.t hopping condition. ii) **Robustness against perturbations:** In perturbed movement, we do similar analyses, but this time with respect to perturbation properties (moment of occurrence, magnitude, and direction of perturbation). In these analyses, we expect to find the muscle reactions to perturbations either based on changed muscle activation (e.g., control) or muscle dynamics.

T1.4 (PostDoc & PhD): The outcomes of Task 1.3 are employed to find a criterion for optimal actuator design in the next WP. Here, we employ inverse optimal control approach [51,52] to find a cost function of a biological actuator, which will be later used in optimal EPA design. In general, locomotion control can be formulated as an optimal control problem. Then the actuator (e.g. muscle) forces will be determined by optimizing a cost function. We use our OpenSim model of human hopping (T1.2) to provide the muscle forces for an optimal control problem (finding the relation between system states and muscle forces) and to approximate the corresponding cost function that should be minimized. Based on this inverse optimal control method, we derive a cost function for designing optimal EPA for hopping. Note that the outcomes of the robustness analyses (T1.3) are also employed to find the cost function. Hence, the final controller utilizing the cost function will be an optimal controller, which is robust against perturbations (e.g. changed ground level). Robustness of optimal controllers is often expected as it can be also observed in traditional optimal controllers like the LQR (linear quadratic regulator) [57, 58]. Therefore, the outcome of this task will be a combined cost function (comprising energy efficiency and robustness), which describes the overall function of human muscles in perturbed as well as unperturbed hopping. We utilize this cost function in WP2 to design the optimal EPA for hopping in place.

With these tasks we are providing the requirements for designing actuators for the first locomotion sub-function (bouncing) and for developing and verifying a bio-inspired actuator design method for locomotion, which will be completed in the next WP. Successful accomplishment of this work package opens a new horizon in bio-inspired actuator design.

2.3.2.2. Work Package 2: EPA Design and control

Hypothesis: *Optimal EPA design and control enable mimicking the performance of muscles in hopping.*

WP2	**EPA Design and Control (Months: M6-M24)**
Purpose	Develop and control optimal EPA actuators for human-like hopping.
Tasks	**T2.1 (M6-M9)** Developing a basic set-up of EPA actuator (EPA-Testbed).
	T2.2 (M9-M15) Building a validated simulation model of the hybrid actuator with the ability to investigate different arrangements of EM and PAM.
	T2.3 (M16-M18) Designing an optimal arrangement and control for a specific task (e.g., periodic joint movement) in the simulation model, based on developed criterion (cost function) for a muscle, found in WP 1.
	T2.4 (M19-M24) Implementing the design and control developed in T2.3 on EPA-Testbed and verifying the applicability of the design approach.
Milestones	**M2.1** Developing a validated dynamic model of PAM and EPA.
	M2.2 Identifying optimal EPA design in simulation.
	M2.3 Design and control of optimal EPA.
	M2.4 Developing a verified methodology for bio-inspired actuator design and control.

The goal of this WP is developing and implementing the novel optimal EPA actuator. We expect that - depending on their specific functions - different muscles can be translated into matching EPA designs. The EPA design, which represents the muscle behavior (and its response to perturbations) best, will be identified. To simplify control, we adjust compliance using PAM [26] and apply position control to EM. The EPA will be designed to work efficiently and stably in different hopping conditions. As multiple human muscles share work at a single joint we first optimize EPA design for different muscles separately. In the WP3 the single-joint knee extensor and flexor are utilized for hopping. The optimal EPA is designed within the following four steps, (T2.1-T2.4, in above table):

T2.1 (PhD & students): We develop a basic set-up (EPA-Testbed) for (i) identification of the actuator model and (ii) implementing and evaluating different EPA design and control matching different muscles. Together with HOSODA lab, we set up a serial EPA (Fig. 2). Using XPC-target control (MATLAB) we can control both PAM and EM using Simulink programs. With this set-up we are able to identify the PAM model (target (i), see above). As there is no comprehensive dynamic model of PAM in the literature we need to identify the muscle model. For this, we are inflating the muscle with a fixed amount of air in a no-load condition and closing the valve. Then, we exert different force profiles with the EM and measure the pressure and muscle length. Using these measurements, we can identify the relationship between PAM length, PAM pressure, and PAM force. For a more comprehensive dynamic model, we repeat this measurement for different amounts of air inside the muscle (i.e., the different pressures at no-load condition). To continuously control the air pressure, we measure the airflow with a flowmeter (not included in the existing setup). The developed dynamic PAM model will be integrated into the EPA-Testbed model in the next task.

The second application of the EPA-Testbed is implementing the optimal design and control. For this, we add an additional lever arm (hinge joint) with known parameters (e.g., inertia) and equipped with an encoder. The EPA-Testbed will be extended to permit parallel and antagonistic muscles. This redesign will be made jointly with our scientific consultants Dr. Hosoda and Dr. Vanderborgth.

T2.2 (PostDoc & PhD) In this task, we will build a precise dynamic EPA model[1] with the ability to change the arrangement of PAM and EM. PAM and EM models will be derived from the experiments in T2.1 and some verification experiments are designed to be implemented on EPA-Testbed to validate the model prediction. The models can be used in the next task as replacements for human muscles in the muscular model developed in OpenSim (T1.2) for comparison between EPA and biological actuators.

T2.3 (PostDoc & PhD) After developing the verified EPA model, we search for an optimal PAM / EM arrangement in EPA (e.g., serial, parallel and antagonistic) and a matching control for a specific task (e.g., periodic movement with a certain frequency/amplitude). The goal is finding the optimal design for representing individual muscles in human hopping based on results of WP1. For each muscle, we optimize the cost function found in T1.4 for different EPA arrangements. We expect different EPA arrangements for different muscles. Then, we design some evaluation tests in which we compare the muscle and the actuator in performing a specific task e.g., tracking a periodic joint movement or a force profile (see Sec. 1). The evaluation tests are designed (for each muscle) using the OpenSim model in which the muscles (biological actuators) and EPAs are compared. For this comparison we use scaled descriptions (with dimensionless parameters) for models with EPA and human muscles to represent tracking errors, energy efficiency and robustness against perturbations.

T2.4 (all) We transfer the outcomes of T2.3 to the EPA-Testbed by implementing and testing optimal EPA arrangements representing selected human muscles in hopping. We implement the evaluation test in simulation (T2.3) now experimentally on EPA-Testbed and compare the results of simulations and experiments. Accordingly, we will have an evaluation of EPA in the EPA-Testbed compared to the corresponding estimated human muscle performance. We expect to find similar results in simulations and experiments of EPA besides comparable performance as in the corresponding muscles.

With this **WP** we aim at establishing a novel bioinspired actuator design method for locomotion. This method could later be applied to other actuator types and other tasks.

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[1] Preliminary steps of building this model were already performed in collaboration with a Ph.D. student (Hirofumi Shin) from HOSODA Lab, who visited the Lauflabor recently (see Sec. 1 for details). *With this EPA model, we showed that appropriate adjustment of PAM helps reduce energy consumption in the electric motor for a periodic movement. Hence, for a periodic movement with a desired frequency and magnitude, an optimal value for the air pressure can be found, which results in minimum effort in EM. More details can be found in the paper submitted to ICRA2017.*

2.3.2.3. Work Package 3: EPA-Hopper Demonstration (EH)

Hypothesis: *Compared to SEA, EPA provides advantages in efficiency, robustness, and energy management (e.g., adjusting hopping height) in 1D hopping.*

WP3	**EPA-Hopper demonstration (M21-M36)**
Purpose	Demonstration and evaluation of EPA-based hopping.
Tasks	**T3.1 (M21-M25)** Setup EPA-Hopper based on MARCO-2 with EPA at knee.
	T3.2 (M24-M30) Implementing and testing stable hopping strategies in EPA-Hopper (based on energy management concepts e.g. VLS, ESLIP).
	T3.3 (M31-M33) EPA-Hopper experiments for selected hopping conditions (height and frequency) and comparison to human hopping (T1.1) regarding efficiency and performance.
	T3.4 (M33-M36) EPA-Hopper experiments with ground level perturbations and comparison to human hopping (T1.1).
Milestones	**M3.1** Successful implementation of energy management models in EPA-Hopper with segmented legs.
	M3.2 Successful implementation of distributed control of stiffness and rest-length realized by PAM and EM, respectively.
	M3.3 Demonstration of human-like hopping performance with optimal EPA.

Bouncing as used in 1D hopping can be realized by adjusting the stiffness and the rest length of a compliant leg actuator (e.g. extensor muscle, EPA). This work benefits from previous experiences on MARCO-Hopper (Fig. 5a, [47,48]). With MARCO-Hopper, different strategies for energy-stable 1D hopping based on simulated spring-like leg function were investigated. Here, we use MARCO-2 which comprises a segmented leg with the ability to use different types of joint actuation (Fig. 5b,c). With MARCO-2 we investigate the advantages of EPA compared to SEA and direct drive for hopping and test our hypothesis for WP3 (see above) by exploiting stiffness adjustment through PAM. We expect the following advantages of the EPA design compared to SEA in 1D hopping:

1. With adjustable stiffness, energy stability (e.g., constant hopping height) can be easily achieved in an efficient way and does not rely on losses caused by damping or friction.
2. With adjustable parallel stiffness (through PAM), force/torque requirements can be reduced, enhancing the efficiency of hopping (e.g., with pre-tensioned PAM as a passive elastic element). This may result in reduced EM peak power (smaller EM) and/or energy.
3. The actuator stiffness in EPA (adjusted by PAM air pressure) can be emulated in SEA with motor control. However, the stiffness control approach (in SEA) lowers performance and stability while two outputs (e.g., impedance-position or stiffness-rest length) needs to be controlled by just one input (EM torque). This is simpler in EPA with separate access to position and stiffness.
4. With adjustable stiffness (through PAM), energy losses (e.g., due to damping, friction) can be compensated, reducing landing-takeoff asymmetry [60] in bouncing gaits.

We test different control strategies for EPA-based hopping with and without ground level perturbations in EPA-Hopper and compared to other actuators and to human hopping (T1.3) regarding energy management and robustness against perturbations. The following steps (T3.1-T3.4) will verify the WP3 hypothesis:

T3.1 (all) With support of Dr. Beckerle (IMS) we develop the EPA-hopper with the sensors presented in T2.2. The control unit and interface will be updated (with XPC-target instead of Labview). We add attachment points to allow for different EPA arrangements.

T3.2 (PostDoc & PhD) We implement hopping control strategies on EPA-Hopper. This includes energy management methods (e.g. ESLIP and VLS). A previously developed model of MARCO-2 [61] will be updated to represent EPA-Hopper. The hopping controller will be first implemented on the simulation model and then on the robot. In this task, the goal is generating stable hopping (at least 25 steps) on the robot with each method. Ph.D. candidate implement the controllers on the robot with help of the PostDoc and IMS group members. This is similar for the next two tasks as well. Dr. Vanderborght and Hosoda support us in design and control of actuators in EPA-Hopper.

T3.3 (PhD & PostDoc) We perform experiments on EPA-Hopper with different hopping controllers and different hopping conditions (e.g. height, frequency). We compare the results to human hopping experiment results. We do the same for SEA and direct drive and compare the performance and efficiency of different actuators and controllers. We expect to have higher efficiency with EPA with comparable performance to human hopping.

T3.4 (PostDoc & PhD) We repeat the steps of T3.3 with ground level perturbations. Here, we compare the robustness of different actuators and controllers against ground level perturbations, in addition to efficiency and performance. Note that the controller is the same in perturbed and unperturbed hopping experiments to satisfy both high efficiency and robustness against perturbations as targeted in WP1. We compare the results to human perturbation recovery as well.

2.4. Data handling

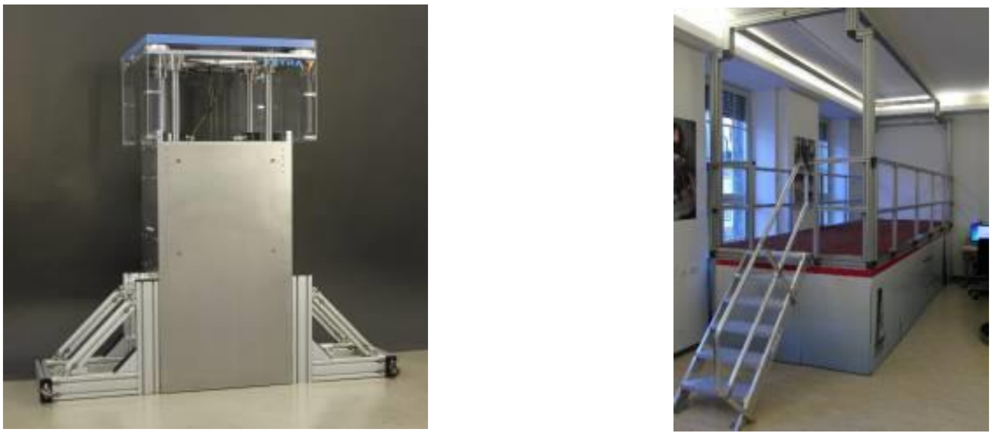
Data measured from human subjects and also hardware experiments will be stored at the lab data management system CIARA (with the user and project management) for later use, which is set up at the Lauflabor lab server. The developed models and corresponding data sets will be made open source. The personal information will be encrypted to ensure the user's privacy.

2.5. Other information

EPA-Hopper and its relation to the MARCO-Hopper 2: The EPA-Hopper setup is planned as an extension of MARCO-2, which was developed in close collaboration with IMS (Institute for Mechatronic Systems) with local funding at TU Darmstadt. For the experiments and system modifications in the EPA project, we will benefit from these experience, expertise, and facilities at IMS in the field of bio-inspired robotic systems. Currently, we work together on MARCO-2. A simulation model of MARCO-2 is developed and different controllers are implemented in a jointly supervised master study [61, 50, 55]. This research will be extended with the new EPA in this project (WP3), which is envisioned to be supported by IMS.

2.6. Explanations on the proposed investigations (experiments on humans, human materials or animals)

The human experiments will be done with the approval of the Ethics Committee at TU Darmstadt. The anonymity of subjects is guaranteed by using subject codes. About 15 Participants will be selected in the hopping studies without any specific illness with physical and mental resilience. The experiments will be performed at the Lauflabor gait lab on a walkway with a perturbation platform, (Fig. 6).



(a) (b)

Figure 6. Pictures of the (a) perturbation platform and (b) walkway.(from http://lauflabor.ifs-tud.de/)

2.7. Information on scientific & financial involvement of international cooperation partners

This project does not aim at any specific commercial product development but focuses on basic research questions.

Prof. Koh Hosoda from Osaka University in Japan, an expert in developing (design, manufacture and experiment analysis) bio-inspired bipedal robot using pneumatic actuators [25] will support the hardware setups design as a “Mercator Fellow” in this project. He contributes to the design and control of the two hardware testbeds. With such a joint work, we benefit from strong expertise in pneumatic actuation used in robotic legged systems with specialized user-friendly software. The valuable experience of the HOSODA Laboratory (http://www.robot.ams.eng.osaka-u.ac.jp) in building PAM-based bipeds (and humanoids) with the focus on bio-inspired legged locomotion for more than 10 years will help us cope with hardware issues in developing robotic setups and doing hardware experiments.

Prof. Bram Vanderborght from Vrije Universiteit Brussel is a visiting researcher with expertise in actuator design and development for robotic applications, especially in legged locomotion (http://mech.vub.ac.be/multibody/members/bram.htm). During his Ph.D., he studied the use of adaptable compliance of pneumatic artificial muscles in the dynamically balanced biped Lucy [23]. His experiences in working with different robots (e.g., HRP2 and iCub) and different types of actuation systems in robotics (PAM, series-parallel elastic actuation and VIAs like Maccepa [12]) helps us in designing EPA.

Dr. Philipp Beckerle from IMS (Institute for Mechatronic Systems) in TU Darmstadt is a collaborator in developing EPA-Hopper robot. Dr. Beckerle is a mechatronics engineer and is an expert in human-machine-centered design and actuation of lower limb prosthetic systems. He was involved in the design and manufacturing process of MARCO-2. We have started modeling and experimental investigations of implementing bioinspired control strategies for hopping on this robot. In addition, Lauflabor and IMS have worked together in different projects (e.g., currently in a lower limb prosthetic sockets project). Dr. Beckerle will advise us in the transfer of biomechanical models into hardware/actuator design and control approaches.

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