Hybrid Electric-Pneumatic Actuation (EPA) design can support robustness and efficiency in hopping

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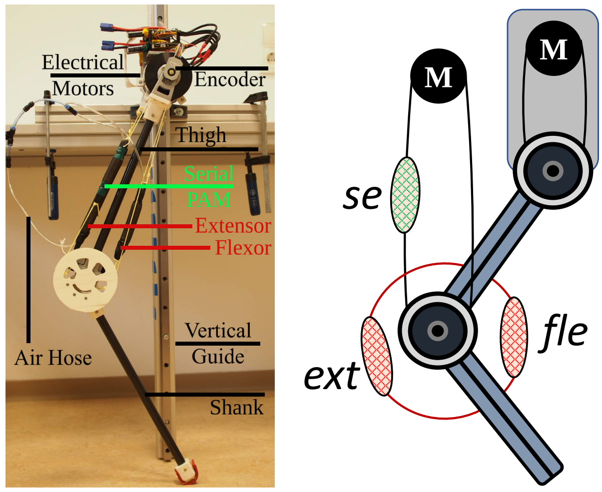
1 Introduction

Actuators are the integral part of any robotic control systems. Out of the many different types of actuators, electrical motors stand out for having precise position tracking capabilities with a high bandwidth. Yet, the rigidity of these actuators preclude them from having safe human-robot cooperation and being energy efficient. Furthermore, when compared to their biological counterparts (i.e., muscles), it is observed that despite their higher power density, systems equipped with electrical motors can not function with the same level of dexterity, agility or versatility as biological systems. As an alternative, Pneumatic Artificial Muscles (PAMs) which closely resemble the function of biological muscles [1] have shown to be very favorable for legged locomotive systems [2]. PAMs are cheap, inherently compliant and easy to implement in different arrangements. Moreover, they offer a high power to weight ratio. Nevertheless, the downside of PAMs is that they possess a low bandwidth and precise positioning is challenging. Therefore, our solution lies in the combination of electrical motors and PAMs as suggested by previous studies [3]. Accordingly, in this work, we employ the electric-pneumatic actuation in a two-DoF legged robot to investigate the potentials of this design.

2 Robot Perturbation Experiment

We conducted a perturbed hopping experiment with a two-DoF robotic leg (EPA-Hopper-I); see Figure 1a. This robot is equipped with two electrical motors for actuating the knee and hip joints, and three PAMs; one in series with the knee motor (*se*), and two in parallel with the knee joint -*ext* and *fle*- for extending and flexing the knee, respectively; see Figure 1b. The bio-inspired hopping controller from [4] was applied for controlling the hip and knee motors. Before the experiment, each PAM pressure was tuned to a predefined constant value (i.e., 0.4 MPa, 0.5 MPa, and 0.6 MPa). Then, all valves were closed during the experiments. EPA-Hopper-I started hopping after it was dropped on a wooden block from 10 cm height. To introduce the ground dropping perturbation during hopping, the wooden block (thickness 5 cm) was removed during the flight phase after 30 hops. The experiment was terminated after another 30 hops. Ground reaction forces were measured by a Kistler force plate at 1 KHz and a 3D Qualisys motion capture system recorded the robot's hip and foot positions at 500 Hz.



(a) (b)

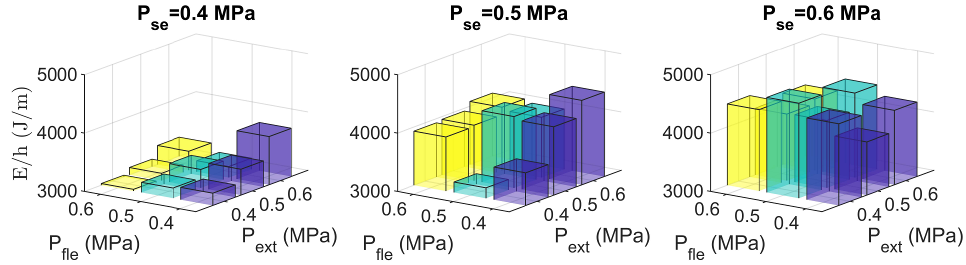
Figure 1: EPA-Hopper-I: A two-DoF leg co-actuated by two electrical motors and three pneumatic artificial muscles acting on the knee joint. *se*, *fle*, and *ext* indicate the serial, flexor, and extensor PAMs, respectively.

3 Results

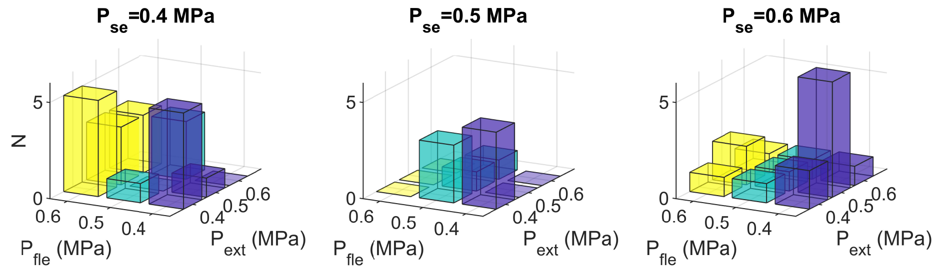
Here, we explain the findings of the perturbation experiment and analyze the effects of PAMs in terms of energy consumption, and robustness with the main focus on the serial PAM role. The role of parallel PAMs were partly presented in our recent work [5].

3.1 Normalized hopping energy consumption

The normalized hopping energy consumption is defined as the ratio between the motor electric energy consumption (E) and the stable hopping height (h). Hopping height is also defined as the difference between the maximum hip height (apex) during the flight phase and the hip height at the touch-down moment, averaged over 15 consecutive hops. The mean normalized hopping energy consumption of the 15 hops before the perturbed hop is shown in Figure 2a. The results show that, in general, low pressure in the serial PAM results in lower normalized energy consumption. The lowest normalized energy consumption is 3028 J/m ($P_{se} = 0.4$ MPa, $P_{fle} = 0.6$ MPa, $P_{ext} = 0.4$ MPa). Interestingly, the normalized energy consumption of the highest hopping height which occurs at PAM pressure set-



(a)



(b)

Figure 2: Experiment results on EPA-Hopper-I: (a) Normalized energy consumption (E/h) to the hopping height with different PAM pressure settings. (b) Hopping robustness in terms of the number of hops (N) required to recover from the perturbation. The subscripts *se*, *fle*, and *ext* indicate the serial, flexor, and extensor PAMs, respectively.

tings of ($P_{se} = 0.5\,\text{MPa}$, $P_{fle} = 0.5\,\text{MPa}$, $P_{ext} = 0.4\,\text{MPa}$)[1] is relatively low (3179 J/m), as shown in Figure 2a.

3.2 Hopping robustness

The required number of hops to recover from perturbation is used to quantify the hopping robustness. After the perturbed hop, the number of hops is counted till the hopping height is within the 5% of the hopping height before the perturbation. The results are shown in Figure 2b and they show that EPA-Hopper-I can reach stable hopping again for all PAM pressure settings after the 5 cm ground dropping perturbation. The medium pressure in the serial PAM yields the most robust hopping behavior ($P_{se} = 0.5\,\text{MPa}$, average $N = 1$; $P_{se} = 0.6\,\text{MPa}$, average $N = 1.78$; $P_{se} = 0.4\,\text{MPa}$, average $N = 2.33$). It requires more hops (4-6 hops) to recover from perturbations if the pressure in the serial PAM is low and the pressure in the flexor PAM is high. On the contrary, EPA-Hopper-I can reach stable hopping right after the perturbed hop if the pressure in the serial PAM is medium and the pressure in the flexor PAM is high.

4 Conclusions

In this work, we investigated the role of pneumatic artificial muscles on the energy consumption and robustness of the EPA-Hopper-I. We showed that different PAM pressure settings can have different effects in the hopping performance in terms of hopping height, energy consumption, and robustness. Adjustment of the serial PAM (SE) can significantly affect efficiency, performance and robustness as i) the softest SE yields the most efficient hopping, and ii) SE with Medium stiffness (middle pressure) provides the most robust and highest performance (not shown). Further, iii) both extensor and flexor PAMs influence efficiency, performance and robustness, but the effect is depending to the SE stiffness. These analyses can support the effectiveness of the EPA design and help better understand the functionality of human musculoskeletal system in hopping gait. Such studies can be extended to other gaits.

[1] The highest hopping height achieved with EPA-Hopper-I was 11.3 cm ($P_{se} = 0.5\,\text{MPa}$, $P_{fle} = 0.5\,\text{MPa}$, $P_{ext} = 0.4\,\text{MPa}$) and the lowest hopping height was 7.1 cm ($P_{se} = 0.4\,\text{MPa}$, $P_{fle} = 0.4\,\text{MPa}$, $P_{ext} = 0.6\,\text{MPa}$).

5 Acknowledgment

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