Adjustable compliance and biarticularity could improve hopping efficiency and robustness

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1 Introduction

Biological locomotor systems are examples of efficient and adaptable systems to be used as blueprints to design and control robots. Humans are capable to adapt rapidly to different movement tasks and environments. Depending on the movement target different hopping performance and control patterns could be observed. In pursuing this versatility, different actuators (e.g., Variable Stiffness Actuators (VSA), Pneumatic Artificial Muscles (PAM)) and control strategies (e.g., Force Modulated Control (FMC), Neuromuscular Reflex Control, Impedance Control) have been developed in the bio-inspired robotics field [7]. Nonetheless, control embodiment through morphological computation is a key factor that deserves more attention in the legged robot development. Besides, bioinspired robots can complement simulation studies for verifying identified human motor control strategies in real systems.

This work investigates how embodiment can affect the performance on a 3-segmented hopping legged robot [4]. We have developed the hybrid electric-pneumatic actuation (EPA) [1] system to address control embodiment through a combination of electric motors and pneumatic artificial muscles (PAM). In this study, the EPA-Hopper-II was used to explore the impact of different muscle morphology in the ankle joint, Figure 1a. Ergo, the role of monoarticular and biarticular [2] ankle muscles on hopping efficiency and robustness against perturbations [6] are investigated at two different frequencies. The outcomes of our experimental robot studies can improve our understanding of human motor control in hopping, as well as developing more versatile robots.

2 Methods

The EPA-Hopper-II is a 3-segmented legged robot. Out of the three joints, only the hip and knee joints are actuated by electric motors as shown in Figure 1b. The ankle joint is kept passive by the introduction of Pneumatic Artificial Muscles (PAMs). The pressures of the PAMs responsible for ankle flexion and extension, are kept constant for each trial. In addition, a complementary PAM is attached to contribute to the knee extension, taking the role of the Vastus muscle (VAS). This parallel knee PAM could restore part of the energy absorbed at the landing and provide robot safety from collapsing and its pressure is kept constant in all trials. A Kistler force plate and Qualisys cameras are integrated to capture the ground reaction forces and robot kinematics. The control algorithm is divided into stance and flight phases at hip and knee joints. During the flight phase, position control is implemented at both joints. While in the stance phase, the hip motor is turned off and for the knee joint, a Virtual model control (VMC) [3] emulating a spring between the hip and ankle is applied. The controller is kept constant for all experiments at the same frequency.

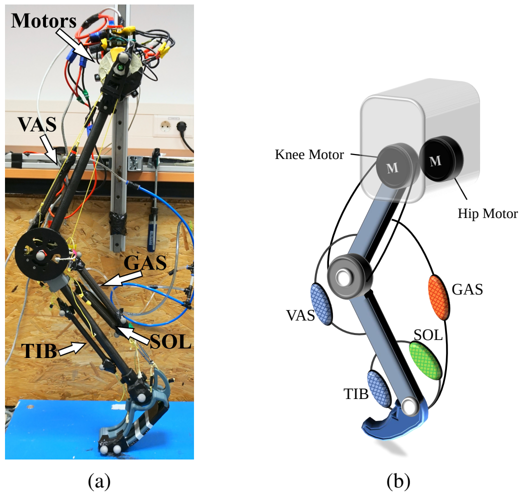

Figure 1: EPA-Hopper-II

Six different configurations have been studied. Consisting of the combination of Tibialis Anterior with Soleus or Gastrocnemius. Pressurized at low (2 bar), medium (4 bar) or high (6 bar) pressure. For each ankle configuration, the experiments were repeated two times. Each trial starts with pressurization of the PAMs to the given pressure while keeping the rest ankle joint at 130°, and consequently closing the valves for all trials. Subsequently, the robot is dropped and let to hop on a 15cm wooden block. After 15 hops, the wooden block was removed, by an electric motor, during the flight phase, and the robot hops for extra 15 hops until the trial is terminated. In this paper, robustness has been assessed by counting the number of hops required to return to stable hopping (within a 5% error) after the perturbation occurred. While efficiency as the power average in steady-state, allowing to compare the energy outcome over time regardless of discrepancies in hopping frequency.

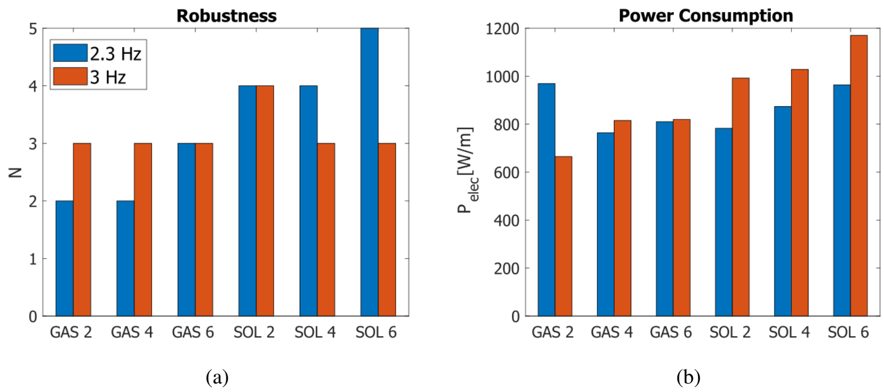

Figure 2: EPA-Hopper II performance at different configurations, pressures and frequencies. (a) Number of hops to recover to stable hopping. (b) Power consumption at steady-state

3 Results

Two different performance factors are analyzed in our experiments: efficiency and robustness against perturbation.

3.1 Robustness

Figure 2a shows the required hops to recover from perturbation as a measure of robustness. A higher robustness is generally observed while using the biarticular GAS muscle. For slow hopping at 2.3 Hz, a lower PAM pressure provides a faster recovery to perturbation. Nonetheless, this pattern changes for fast hopping at 3 Hz using monoarticular SOL PAM.

3.2 Efficiency

The efficiency in form of power outcome can be seen in Figure 2b. Overall, lower power consumption is noticed for a lower frequency, 2.3 Hz. And for the same pressurization, a TIB-GAS combination provides an advantage over TIB-SOL configurations. The only exception to this observation is when the GAS is too soft (pressurized to 2 bar).

4 Conclusions

In this study, different ankle muscle configurations have been investigated regarding power consumption and robustness. We showed that the appropriate body morphology and mechanical properties can improve robustness and efficiency needless to change the controller. This is an application of control embodiment using morphological computation. The analyzed results show a prominent impact of the Gastrocnemius muscle in both performance factors. This could have resulted from its biarticular nature and capability to transmit energy and synchronize knee and ankle joints.

It can also be observed that pressure (indeed stiffness) can considerably impact energy consumption. For example, too soft GAS (2 bar) cause higher energy consumption in slow hopping at 2.3 Hz. One reason could be insufficient ankle impedance provided by soft GAS. This critical stiffness at ankle joint was also found in other studies [5]. Another interpretation could be tuning the natural frequency of the robot by changing the muscle's mechanical properties (here, compliance).

Another observation is that no single solution provides the best performance in all tasks. Our findings on the impact of the GAS and pressure are advantageous; nonetheless, a further study or simulation with a larger sweep of frequencies or pressures could complement these findings. Moreover, a combination of SOL and GAS is expected to provide a higher morphological advantage which can be investigated in future studies.

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