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# A methodology to estimate the cost of transport of a hexapod robot based on single leg performance

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## 1. Introduction

Legged robots are used as models for animal behavior studies (Manoonpong et al. 2021). Computer simulations appear to be too simple to conveniently model the complexity of the interaction between robots or animals and their environment. Robotic platforms are therefore relevant for modeling navigation or locomotion tasks in real outdoor conditions (Manoonpong et al. 2021) because each robot's leg can be unexpectedly disturbed by uneven terrain or uncontrolled physical parameters.

Unlike simulations, real robots have defects, such as structural weaknesses or energetic limitations. Previous research works tended to minimize the energetic consumption of walking machines (Roy and Pratiharl 2012): either by performing optimization on a robot dynamic model or by measuring energetic parameters on the robot itself (Luneckas et al. 2021). Few studies investigated single-leg performance in order to improve robot design processes by carefully selecting gait parameters, such as stride length (Guardabrazo and Gonzalez de Santos 2004).

On one hand, the analysis of a single leg is challenging, as the performance of the robot depends on many parameters: walking speed, step length, leg mass, robot load, duty factor (ratio of ground contact time to leg step time), inertia and mechanical non-linearities. On the other hand, the process of building an entire robot takes time and is usually accompanied by an increased budget.

In this methodological work, we introduce a new approach to evaluate the electric power consumption of a legged robot, by analyzing a single leg power consumption on a dedicated test bench, which doesn't require any dynamic model of the robot and takes account of the non-linearities of the mechanism. The main idea is to split the measured data in two sets: energy consumption during the propulsion stroke (stance), and energy consumption during the leg return stroke (swing). This approach will be helpful to design and fabricate a low power consumption

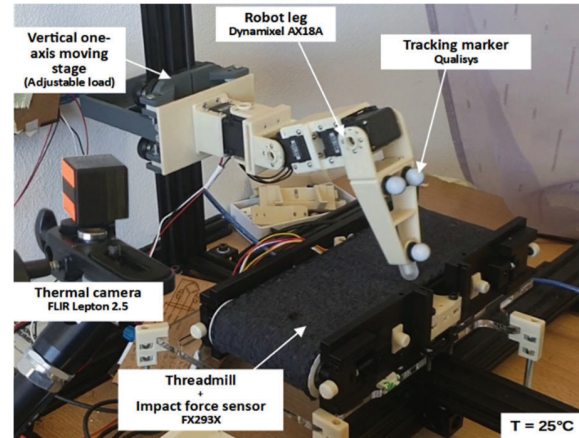


Figure 1. Photograph of the robotic leg test rig.

robotic leg and to evaluate the benefits with respect to a conventional leg design.

## 2. Methods

### 2.1. Conventional hexapod leg

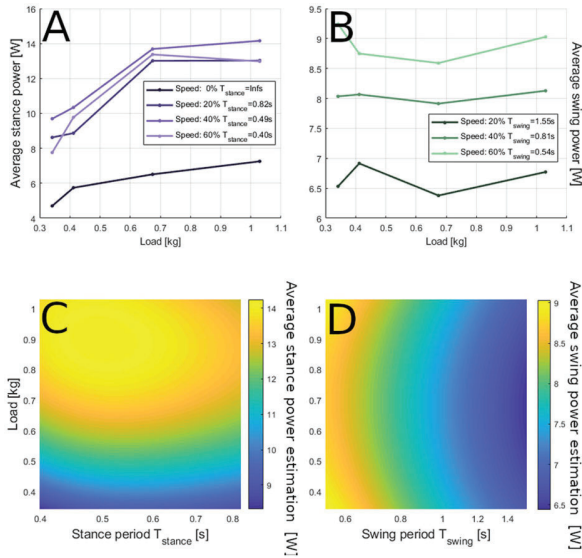
The estimation procedure was performed on a conventional three degrees of freedom hexapod robot leg fitted with three servomotors (Figure 1). The leg was fully 3D-printed and weighed 330 grams. The length of each segment is the following: coxa 50 mm, femur 83.4 mm and tibia 120 mm (Figure 1).

### 2.2. Test bench structure

A specially built test bench was used to measure the performance of the legs (Brodoline et al. 2021). Composed of a vertical one-axis moving stage, representing the attachment to the body, and a freewheel treadmill, mimicking ground movement during the walk. The setup is surrounded by three motion capture cameras, Qualisys Miquis M3, providing the leg tip position during the walk. Power consumption was measured by a current clamp, connected to a NI-USB 6211 acquisition device. The test bench was kept at a temperature of 25°C, controlled through a FLIR Lepton 2.5 thermal camera. Additional force sensors are present under the treadmill plate to make the main computer able to synchronize the kinematic and energetic data.

### 2.3. Experimental procedure

The measuring procedure consists of multiple sessions of walking, under various loads, fixed at the level of the moving stage. For each session, the walking leg follows a pre-programmed walking motion, i.e. at a fixed trajectory, stride length and duty factor. For



**Figure 2.** A. Average measured electric power of the stance phase versus load changes. B. Average measured electric power of the swing phase versus load changes. C. Estimation of the average power consumption during a stance phase. D. Estimation of the average power consumption during a swing phase.

each available speed, the test bench records kinematic and energetic data for 15 minutes, which corresponds to a typical duration for this kind of robots. Once all the desired sessions ended, the main computer calibrates the data and estimates the curves (Figure 2).

### 3. Results and discussion

Figure 2 shows the leg’s performance. The surface plot Figure 2C, fitted through bivariate analysis, gives us, for any walking speed and load, the corresponding average power consumption during the stance phase, i.e. when the leg is touching the ground and supporting the robot’s weight. The speed value, given by the stance period, i.e. the time of the ground contact, provides the ability to predict the power consumption for any walking duty factor of the leg.

Figure 2D illustrates the swing phase power consumption, which is a contactless movement, i.e. when the leg is not supporting the robot’s weight, but is dependent on the load, which can lead to a temperature increase with the transported load.

Starting from the fitted data, we can predict the complete robot cost of transport (CoT), which is a typical value illustrating robot walking efficiency:

$$CoT = 6 \cdot (\overline{P}_{stance} \cdot \beta + \overline{P}_{swing} \cdot (1 - \beta)) / mgv$$

Where  $\overline{P}$  represents the average power of a phase, and  $\beta$  the desired duty factor value.

The estimated CoT for the studied leg is 22.7 at a speed of 0.1m/s and a duty factor of 0.23 with no

load. This value corresponds to the CoT range measured on the same type of robot (Luneckas et al. 2021) where the CoT varies from 25 to 5.75 and equals to  $\sim 10$  for a robot’s speed of  $v = 0.1\text{m/s}$ . This bias may be caused by various parameters such as the leg motion control, the leg structure, or the duty factor.

### 4. Conclusions

In this study, we introduced a new method to estimate hexapod robot performances by developing a methodology to evaluate a single leg. The main contribution of this work is to split acquired data in relation to power consumption in two categories, depending on the walking phase: the stance phase and the swing phase. In each phase, we could therefore identify which robot’s parameter needs to be improved or optimized. Next, this work in progress will allow us to estimate other locomotion performances comprising the evaluation of the cost of transport (CoT) to compare, not only the locomotion gait, but also the intrinsic power consumption of actuators with respect to a conventional reference design.

### Disclosure statement

No potential conflict of interest was reported by the authors.

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