Bio-inspired actuator design for hopping

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1 Introduction

Legged locomotion is a complex motor task. Simplified models can help to understand the mechanical characteristics of the lower limb and its control principles. This work investigates the interaction of a spring and a motor in a series elastic actuator (Fig. 1a) that should mimic knee extension at different hopping frequencies. In particular we are interested in the optimal stiffness of the series elastic actuator to minimize motor energy and peak power requirements. We hypothesize to find increasing optimal stiffness values for increasing hopping frequencies. Further, we hypothesize that energy requirements are lowest at the human preferred hopping frequency. We will use hopping experiments and simulation studies to design and improve the functionality of the EPA-hopper robot (electric-pneumatic actuator, Fig. 1b) with a pneumatic variable impedance actuator [1]. We believe that by adjusting compliance in the EPA-hopper robot we can reduce the consumed energy and peak power when changing hopping frequencies.

2 Methods

2.1 Human Experiments

Eight healthy young subjects were asked to hop in place (20 s) on both legs with predefined hopping frequencies (1, 2 and 3 Hz) and the individually preferred frequency. Kinematics and kinetics were measured by using a Qualisys motion capture system with 10 cameras and two Kistler force plates (Fig. 2a).
OpenSim [2] and its Inverse Kinematics and Inverse Dynamics tool was used to compute the sagittal knee joint angle and the corresponding knee torque (Fig. 2b).

2.2 Knee actuation properties

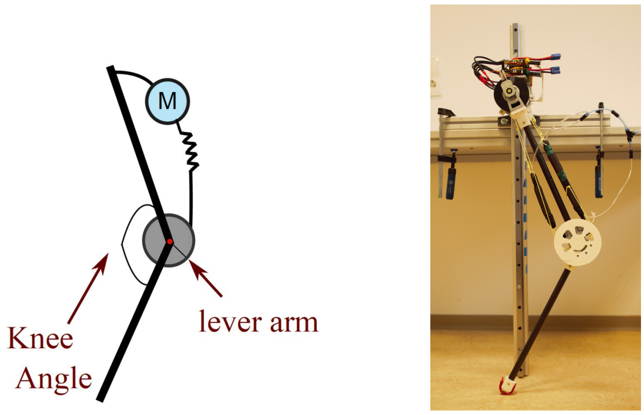
In the EPA-hopper robot, knee extension is implemented by a cable connected to an actuator, which is fixed at the hip joint. The desired force to actuate the knee of the EPA-hopper robot is based on normalized human knee torque divided by the lever arm of the pulley. The lever arm is also used to determine the cable length based on the knee angle.

$$
\begin{aligned}
F &= \tau / L_A \\
\Delta L_M &= \Delta\alpha \times L_A
\end{aligned}
\tag{1}
$$

where F, τ, L_A, L_M and α are cable force, knee torque, knee lever arm, displacement of the cable and knee angle, respectively. Δ is used to show the displacement from the initial positions (e.g., $\Delta L_M = L_M - L_M^0$). Assuming a stiffness K for the serial spring, the displacement in the spring ΔL_S and in the motor ΔL_m can be calculated by

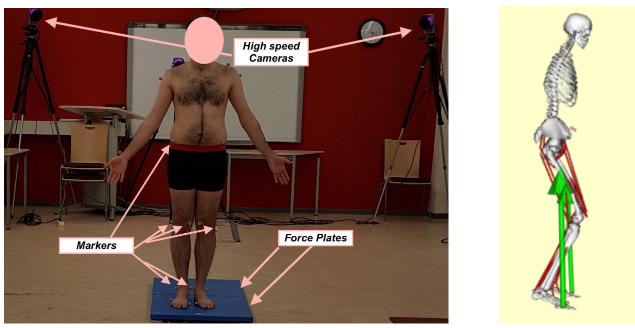
$$
\begin{aligned}
\Delta L_S &= F / K \\
\Delta L_m &= \Delta L_M - \Delta L_S
\end{aligned}
\tag{2}
$$

Therefore, calculating the motor speed by differentiating from motor displacement ($v = \frac{\partial \Delta L_m}{\partial t}$) and multiplying to the generated force (F) the consumed power and consequently the energy requirement of the motor are calculated as fol-



(a) (b)

Figure 1: **(a)** Schematic illustration of the series elastic actuator used to determine the optimal knee spring stiffness. **(b)** EPA-hopper robot with the electric-pneumatic (variable impedance) knee actuator.



(a) (b)

Figure 2: Experimental setup including motion capture system and force plates. **(b)** Used OpenSim model including ground reaction force vectors (green) and nine muscle groups at each leg (red).

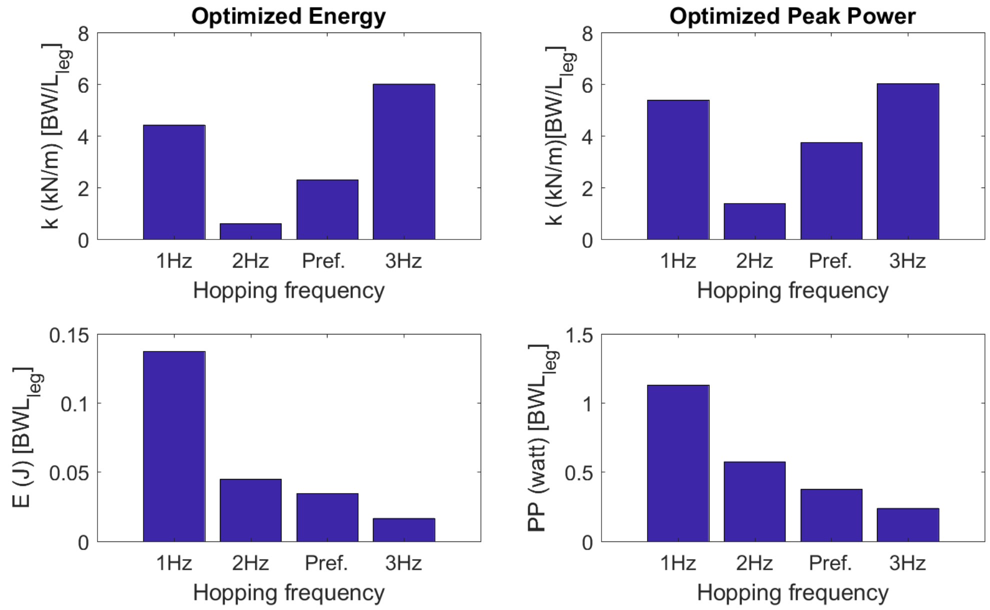


Figure 3: Upper panels: SEA stiffness optimized for minimal energy requirement (left) and peak power (right) for different hopping frequencies. Lower panels: related energy requirements (left) and peak power requirements (right). All the values are normalized with the body weight and leg length.

low:

$$\begin{aligned} P &= F \times v \\ E &= \int P dt \end{aligned} \tag{3}$$

2.3 Optimal serial elastic stiffness

The stiffness (K in Eq. (2)) of the series elastic actuator (SEA) was optimized to minimize the peak power and the energy requirement similar to the approach in [3] for four hopping frequencies (preferred frequency, 1, 2 and 3 Hz).

3 Results

We found that the stiffness K increases with increasing hopping frequency for energy as well as peak power optimization, except for hopping at 1 Hz where high stiffness values were found (Fig. 3). Identified stiffness values are between 0.6 and 6 kN/m (normalized to body weight and leg length). Both required energy and peak power for the motor decreased with increasing hopping frequency (Fig. 3).

4 Discussion

We hypothesized that optimized SEA stiffness results in lowest energy requirement and peak power values at the preferred hopping frequency. However, the highest hopping frequency was identified to require both minimal energy and peak power. As expected, stiffness values were increasing with hopping frequency. Only at 1 Hz subjects seem not to benefit from the elastic energy storage, which resulted in an increased optimal stiffness. The stiffness values for both optimization targets were similar for each hopping frequency. Furthermore, the highest stiffness (at 3Hz) is 10 times larger than the lowest value (at 2Hz) for optimization based on consumed energy. This ratio is 4.3 when the optimization metric is the peak power. With its adjustable pneumatic actuator (by air pressure ranged from 1 to 6 bar), the EPA-hopper robot is able to cover a similar range of stiffness (normalized to body weight and leg length).

5 Conclusion

In this study, we identified the optimal stiffness to reduce peak power or energy requirements for a knee SEA based on human hopping experiments. The results will be used to improve the design of EPA-Hopper robot (Fig. 1b) mimicking human-like hopping. We expect that the optimized stiffness values will not only reduce the energy and peak power requirements but may also contribute to other features such as simplifying the control and improving the stability of hopping. Such aspects will be addressed in future studies.

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References

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