Design of a Series Elastic Actuator driven ankle prosthesis: The trade-off between energy and peak power optimization

seit 1558

Martin Grimmer and André Seyfarth
Lauflabor Locomotion Laboratory, University of Jena
Dornburger Str. 23 D-07743 Jena, Germany
email: Martin.Grimmer@uni-jena.de web: www.lauflabor.de

Lauflabor

INTRODUCTION

During human walking and running a significant part of positive work is provided at the ankle joint [3, 4]. Passive foot prostheses can only give back elastic energy stored during contact. So far, the deficit in active plantar flexion is clearly limiting locomotor function in amputees. To improve the situation, active push-off supporting prostheses for walking (Power Foot One [1], SPARKy series [2]) were developed over the last years. With the SPARKy 3 prosthesis, the potential application to running and jumping is envisioned [2]. To develop such systems it is important to estimate the motor parameters and the energy requirements. This is necessary for direct drive (DD) systems and especially for motor-spring combinations (e.g. series elastic actuators, SEA).

The goal for this study is to estimate to what extent a series elastic element in a SEA can reduce the energy and power requirements in an active ankle-foot prosthesis. In particular we ask how stiffness needs to be adapted to different walking and running speeds.

METHODS

Study 1: 21 subjects walked and ran at five speeds (0.5-2.6m/s) on a treadmill with integrated force sensors (Kistler, 1000Hz). Kinematics were recorded by high speed cameras (Qualisys, 240Hz) [6].
Study 2: 7 subjects ran at 3m/s and 4m/s (same conditions as above) [6].
Ankle torques (normalized to m=75kg, leg length=1m) and angles were calculated to estimate SEA length and force. With this, actuator power and energy (positive + |negative| work) requirements are derived (as in [5], lever arm = 7.3 cm). For each walking and running speed, optimal spring stiffness for minimal energy (ME) and minimal peak power (MPP) was determined.

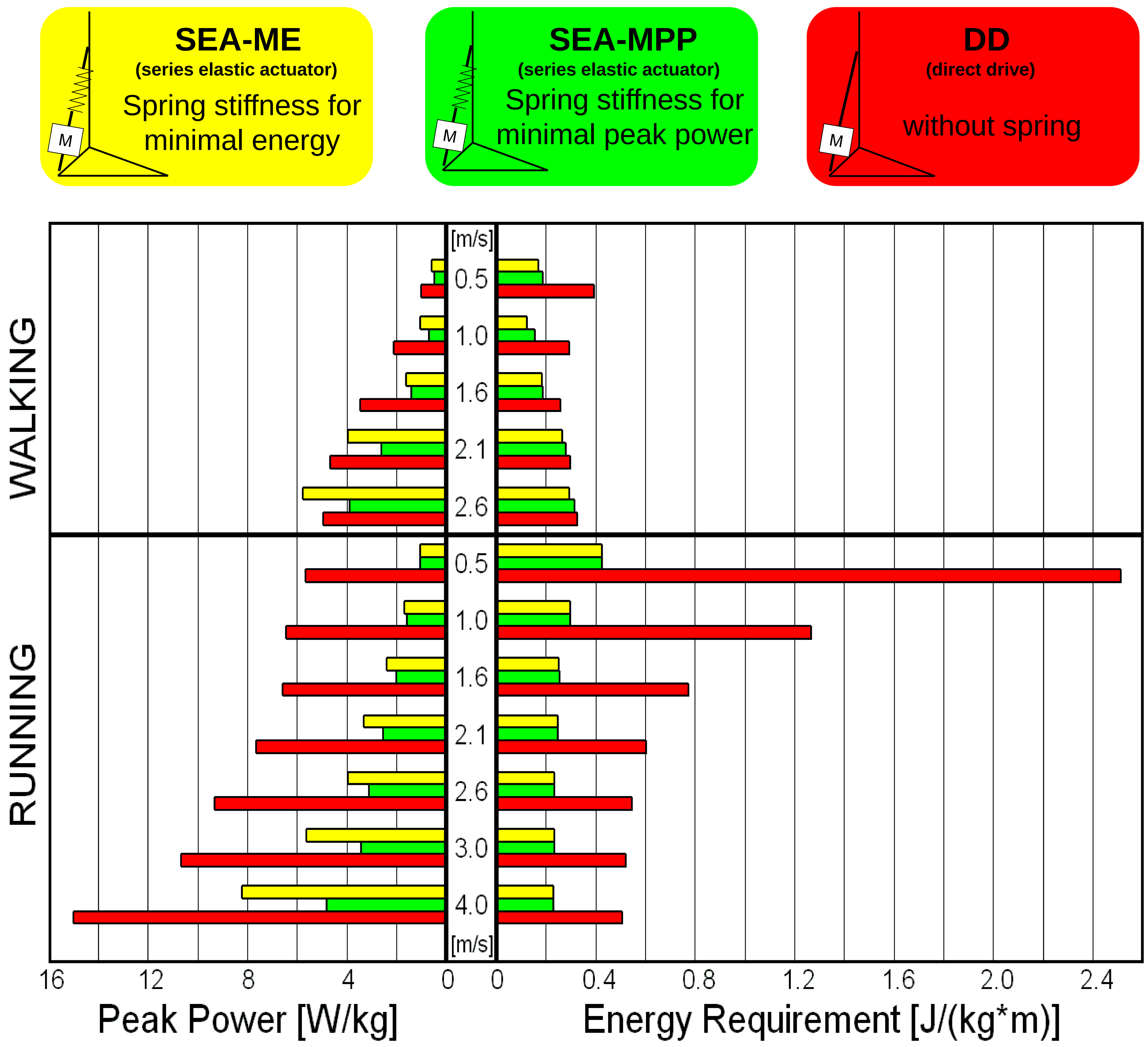

Figure 1: Peak power and energy requirements for walking and running at different speeds to mimic the human ankle behaviour with DD and two SEA configurations

RESULTS

By using an actuator with a serial compliant element (SEA), compared to the direct drive (DD) system, both energy and peak power requirements can be reduced for all measured walking and running speeds.

Energy requirements: With SEA-ME, the energy is reduced by up to 57% (walking at 0.5m/s, 1m/s). There is only a small reduction of 10-11% at the highest walking speeds. In running between 83% (0.5m/s) and 54% (4m/s) of the energy can be saved.

Peak Power: With SEA-MPP, the maximum power reduction is by 82% (0.5m/s running). The smallest reduction (by 22%) is at 2.6m/s walking. It drops by up to 33%-42% (2.1m/s walking and 4m/s running) with SEA-MPP as compared to SEA-ME.

Stiffness: The spring stiffness for SEA-MPP increases with speed (walking: 76-215kN/m, except 0.5m/s, running: 82-112kN/m). For SEA-ME, the stiffness decreases with walking speed (115-54kN/m) and remains nearly constant in running (75-86kN/m).

DISCUSSION

Adjusting the spring stiffness for minimizing energy (SEA-ME) results in a small energy reduction compared to peak power optimization (SEA-MPP). This small energy benefit leads to a significant increase of the required peak power of the motor. In contrast, optimizing the spring stiffness for minimal peak power (SEA-MPP) clearly reduces the power demands as compared to SEA-ME at little additional energy costs.
Thus, optimizing peak power seems to be the primary objective for setting the stiffness of the SEA given that the stiffness can be adjusted to speed. For both gaits (walking and running), spring stiffness should increase with speed. Here, the required stiffness range for minimal peak power is larger in walking than in running. This stiffness increase could be explained by the nonlinear characteristics of the Achilles tendon and a differential, gait-specific co-activation of the triceps surae muscles. To mimic this in a technical device, actuators with nonlinear springs spanning the ankle and partially also the knee could be integrated.

REFERENCES

1. Au, S.K. et al. Powered Ankle – Foot Prosthesis Improves Walking Metabolic Economy. IEEE Transactions on Robotics, VOL. 25, NO. 1, 2009
2. Bellman R.D. et al. SPARKy 3: Design of an Active Robotic Ankle Prosthesis with Two Actuated Degrees of Freedom Using Regenerative Kinetics. Biomedical Robotics and Biomechatronics, 2008
3. Grimmer, M. Biomechanik des Ganges bei Ober- und Unterschenkelamputation – Analyse und mechanische Intervention. diploma thesis, Friedrich Schiller University Jena, 2008
4. Günther, M. et al. Joint stiffness of the ankle and the knee in running. Journal of Biomechanics, VOL. 35, Issue 11, 2002
5. Hollander K.W. et al. Design of the Robotic Tendon. Design of Medical Devices Conference, 2005
6. Lipfert, S.W. Kinematic and dynamic similarities between walking and running. Verlag Dr. Kovac, Hamburg, 2010

Deutsche Forschungsgemeinschaft DFG
DFG SE1042/8