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

Martin Grimmer and Andre Seyfarth
Locomotion Locomotion Laboratory, Unversity of Jena, Dornburger Str. 23 07743 Jena, Germany
martin.grimmer@uni-jena.de, andre.seyfarth@uni-jena.de

1 Introduction

In ankle-foot prostheses a serial spring can assist the motor to reduce peak power (PP) and energy requirements (ER) during locomotion [1, 2]. Similar benefits can be expected for an active knee prosthesis. We compare the situation of a direct drive with a series elastic actuator optimized for minimal ER or for minimal PP.

2 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) [3]. Study 2: 7 subjects ran at 3m/s and 4m/s (same conditions as Study 1) [3].

Knee torques (normalized to m=75kg, leg length=1m) and angles were calculated to estimate SEA length and force depending on the prosthetic model (Fig. 1). With this, actuator power and energy (positive + abs negative work) requirements are derived [1, 2]. For each walking and running speed, optimal spring stiffness for minimal energy (E) and minimal peak power (P) was determined.

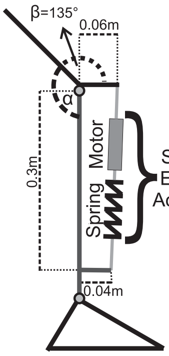

Figure 1: Model of the active knee prosthesis.

3 Results

Peak Power and Energy requirements: 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 fast walking and all running speeds (Fig. 2). For slow walking only a reduction in energy is possible.

Stiffness: For SEA-E in walking optimal stiffness values are between 122-290kN/m. In running between 138-179kN/m. For SEA-P the values in running are between 135-156kN/m. For walking we found a range from 65-363kN/m, while at 1.0 and 1.6m/s a rigid system gives best PP performance. A constant SEA stiffness of around 155kN/m can be used throughout all speeds and both gaits without substantial increases in ER and PP.

4 Discussion

Missing Peak Power Reduction for preferred walking speeds: Surprisingly, it was not possible to reduce PP by tuning the SEA spring for walking at 1.0m/s and 1.6m/s. This can be explained using the power curve in Fig. 3 where no PP reduction in phase E could be achieved by the spring. To reduce ER or PP by tuning a serial spring, a synchronous increase and subsequent synchronous decrease of both SEA force and SEA length would be required (Fig. 4). Such a behavior occurs in phase B (loading) and C (undloading). Other examples are phase D and the transition from phase G (loading) to phase A (unloading). In contrast, in phase E the increase and decrease of SEA force is found in parallel to an on-going increase in length. This action can not benefit from a SEA spring.

Peak Power and Energy requirements: For running, we found that adjusting the SEA stiffness for minimizing energy (SEA-E) results in almost no additional energy reductions compared to PP optimization (SEA-P) whereas for walking ER reductions with SEA-E are possible compared to SEA-P. In both gaits there is only a small increase of PP when optimizing for energy compared to SEA-P. Hence, it is equally appropriate to optimize for PP or for ER when designing the knee SEA. The results are different to similar calculations for the ankle joint [2] in which optimizing PP was the better approach. As there is no optimal stiffness when optimizing PP for moderate walking speeds 1.0m/s and 1.6m/s, SEA-E should be preferred. Then ER benefits of up to 25% could be achieved during walking, the most frequently used gait pattern.

5 Open questions

The motor of the SEA has to damp the motion by generating negative power. How much energy the motor really needs

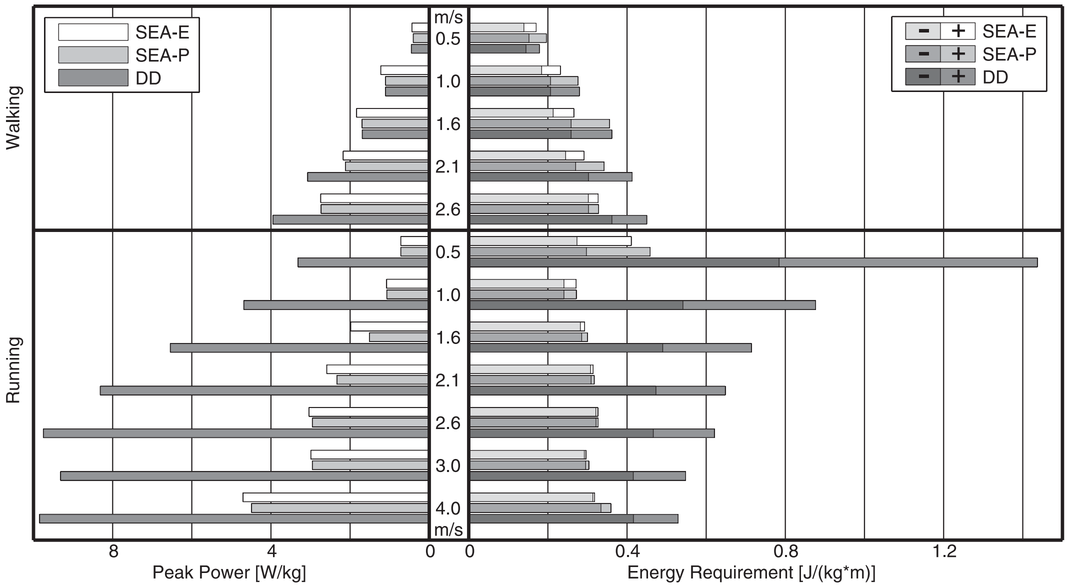

Figure 2: Peak power and energy requirements for walking and running at different speeds to mimic the human ankle behaviour for direct drive (DD), SEA-E (Series Elastic Actuator optimized for energy) and SEA-P (optimized for minimal peak power).

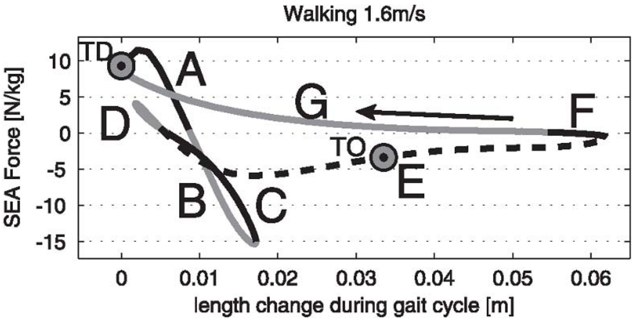

Figure 4: SEA force versus SEA length change (left) during the gait cycle at 1.6m/s walking. TD represents the touch down, TO the take off. A to G represent prominent phases during gait cycle in respect to knee power.

for this resisting behavior in comparison to the calculated values?

References

[1] K. Hollander and T. Sugar, "Design of the robotic tendon," in *Design of Medical Devices Conference (DMD 2005)*, 2005.

[2] M. Grimmer and A. Seyfarth, "Stiffness adjustment of a series elastic actuator in an ankle-foot prosthesis for walking and running: The trade-off between energy and peak power optimization," in *Robotics and Automation, 2011. ICRA'11. IEEE International Conference on*, 2011.

[3] S. Lipfert, *Kinematic and dynamic similarities between walking and running*. Hamburg: Verlag Dr. Kovac, 2010, iSBN: 978-3-8300-5030-8.

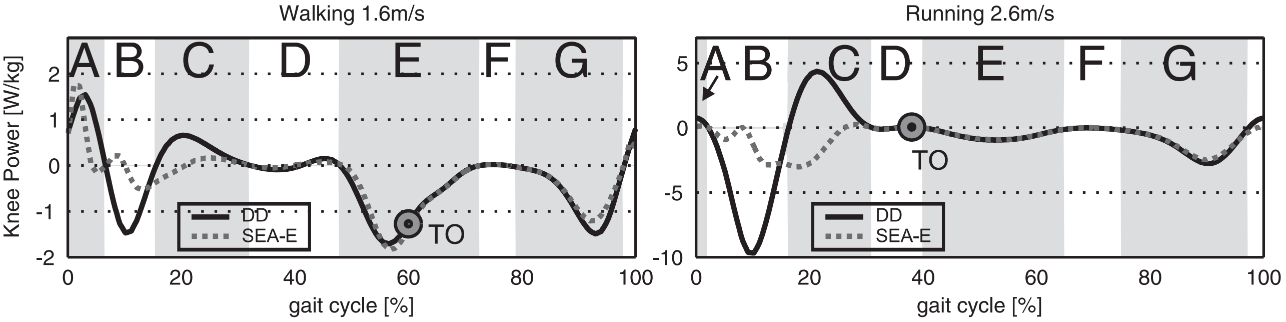

Figure 3: Knee power during gait cycle in walking (1.6m/s) and running (2.6m/s) for a direct drive system (black solid line) and the SEA motor (gray dotted line) optimized for SEA-E. TO represents the take off. A to G represent prominent phases during gait cycle in respect to knee power.