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Research paper

Optimizing the power and energy consumption of powered prosthetic ankles with series and parallel elasticity

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ABSTRACT

Several works have shown that series and parallel elasticity can reduce peak power and energy consumption in prosthetic ankles. Setting the right stiffness of the elastic elements is essential to unlock this potential. In this work, we perform a thorough optimization of series and parallel elastic elements for a prosthetic ankle driven by a geared DC motor. Through simulation, we study the effect of drivetrain limitations and compare different mechanical and electrical optimization objectives. The results highlight the importance of selecting a motor and gearbox in an early stage of the design process. Drivetrain inertia causes peaks in electrical power in the swing phase, which would go unnoticed in an optimization based solely on mechanical power. Furthermore, limitations of the drivetrain and controller reduce the range of applicable springs. This has a direct influence on the optimized spring stiffness values, which, as a result, are different from other works. Overall, the results suggest that, by integrating motor selection into the early stages of the design process, designs can be made lighter, more compact and more efficient.

1. Introduction

Conventional prosthetic ankles are simple devices, enabling amputees to perform basic tasks. In recent years, they have evolved to advanced powered prostheses, approximating as closely as possible the biomechanical behavior of a healthy ankle. The aim is to reduce the problems associated with lower limb loss and amputees using the rest of their body to compensate for this loss. Amputees tend to walk slower and require a larger amount of energy to walk than able-bodied persons [24]. They also show asymmetric gait and joint pains which can be attributed to compensatory behavior at the sound limb [14]. Joint motion, torque and power generation increase at the healthy ankle of amputees when walking [14], effects which lead to a higher susceptibility to develop osteoarthritis in the contralateral limb [17]. By adding active elements in ankle prostheses and being able to provide the same amount of energy of a healthy limb, the metabolic energy of walking can be reduced, as has been shown by Au et al. [2] for the powered ankle-foot prosthesis. Consequently, many active prostheses have been developed in recent years [4].

When looking at the compensatory strategies however, studies have shown the active prosthesis may not lead to a reduction, on the contrary. Ferris et al. suggest that this might be linked to the increased ankle power and range of motion [7]. Adding active elements to prostheses also increases the weight, which is known to increase the energy cost and asymmetry of the gait cycle [13]. This shows the necessity to reduce the weight of the actuation unit, which might be possible

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Fig. 1. Schematic of the actuator with angle definitions. The actuator consists of a Series Elastic Actuator (red) and a unidirectional parallel spring (orange), which is engaged when $\theta \geq \theta_{eq}$. The ankle angle θ is zero when the foot is perpendicular to the leg (denoted by a dashed line). A plantarflexed ankle, as depicted in the figure, corresponds to a negative value of θ. Note that, for clarity of the presentation, the elastic elements are drawn as compression springs in the figure, although they are modeled as torsional springs in the work. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

by investigating series and parallel elasticity for power amplification [15] and energy storage. While directly providing the ankle kinematics with a motor would require a peak power of about 300 W, this can be reduced by adding series elasticity as used in the SPARKy prosthesis [11] and the CYBERLEGs prosthesis [8]. When adding series and parallel elasticity, the peak power can also be reduced as well as the peak torque, like in the Powered Ankle Prosthesis [2]. Simulations show that SEA can reduce the ankle peak power by almost 80% and PEA can reduce peak power by 66% and RMS power by 50% [23].

But what is the optimal combination of parallel and series elasticity in an actuated prosthetic ankle? This is a difficult question, because the optimal stiffness of the series and parallel elastic element are strongly linked, not only to each other, but also to the gear ratio [1]. An extensive analysis was performed by Grimmer et al., who optimized the springs for energy consumption and peak power [10]. They found that parallel springs can be combined with series springs to reduce peak powers, but series springs alone are better for energy reduction. Eslamy et al. presented a similar analysis which also included unidirectional parallel springs [5]. They concluded that a configuration with series spring and unidirectional parallel spring can further decrease the energy demand. However, the optimization in these two works was based on mechanical energy consumption and mechanical peak power, measured on the motor shaft. It therefore disregards motor limitations, drivetrain dynamics and electrical losses. As demonstrated in [19], neglecting these effects can lead to suboptimal results in terms of electrical energy consumption. Motor inertia, for example, can have a significant impact on SEAs for prosthetic limbs [11] and, more specifically, on their optimized stiffness [3]. Farah et al. also observed the importance of the drivetrain in their simulations of the open and closed loop response of an elastically actuated prosthesis [6]. An evaluation of the drivetrain characteristics is therefore gradually becoming an integral part of the design process of powered prosthetic feet [9,22].

Following these observations, in this work, we will simultaneously address the design of motor, gearbox and springs for an actuated prosthesis with series and parallel elasticity. More specifically, we will discuss how the operating range of the selected motor, the gear ratio, the drivetrain inertia and the springs influence one another. We will do this by optimizing the gear ratio and parallel/series elasticity of an actuated prosthesis, taking into account the constraints of the selected motor. Our analysis is not confined to the mechanical domain; we will look at both mechanical and electrical power, and discuss the differences between both. We also contemplate about the potential implications for prosthetic design, suggesting that the performance of the actuator can be improved by a concurrent optimization of springs, motor and gearbox.

2. Methods

In this work, we study the optimal design of Series Elastic Actuator (SEA) equipped with a unidirectional parallel spring. This actuator concept, sketched in Fig. 1, is similar MIT's Powered Ankle-Foot Prosthesis [1] and the one studied by Eslamy et al. [5]. The difference is that, in these works, linear compression springs are used. Consequently, the spring stiffness also depends on the choice of the lever arm. We used torsion springs in order remove this dependency. For the analysis presented in this work, we will work with a 150 W RE40 Maxon motor. Our calculations showed that this is the smallest suitable motor from Maxon's brushed DC motor range. The same motor was used in MIT's Powered Ankle-Foot prosthesis [2] and ASU's Sparky 1 [11].