A Simulation Framework for the Concurrent Optimization of Passive and Active Components of Lower-Limb Powered Prostheses

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1 Motivation

Walking with traditional passive lower-limb prostheses requires additional muscular effort and increased metabolic consumption (1.3-2.5 times the energy expended by a healthy person [1]). This supplementary effort cannot be sustained by many geriatric and dysvascular amputees (the majority of the amputee population [2]) for more than few steps, resulting in a partial or total reduction of the walking ability [3]. To overcome this problem, we need lightweight powered prostheses able to inject controlled amounts of positive energy into the walking cycle in order to improve gait efficiency and increase the independent life of a large number of amputees.

2 State of the Art

Whereas most lower-limb amputees use completely passive devices or semi-active prostheses that actively tune the passive properties at the joints [4], large research effort has been recently devoted to develop active prostheses that can inject positive power into the gait cycle [5]-[7]. From a mechatronics perspective, the greatest challenge faced by researchers consists in achieving the dynamic performance of the human leg, with equal size and mass. Battery-powered servomotors have indeed poor energetic performance compared to the human musculoskeletal system [8]. This deficiency can be partly compensated by exploiting the passive dynamic of legged locomotion (i.e., using elastic elements to store energy in the negative phases of walking and release it during the positive ones). This strategy reduces the torque and power requirements on the actuation, thus allowing smaller and lighter actuators to equal the power provided at the prosthetic-joint level [9].

Nevertheless, the design of the passive elastic elements is commonly optimized to reduce the mechanical work at the actuator output, independently by the actual design and selection of the active components of the prosthesis (i.e. battery and servomotors). As a consequence, a suboptimal configuration of the passive element could be chosen. In fact, minimization of the mechanical work at the joint level does not guarantee minimization of the electrical energy consumption, which in turn determines the minimum battery size for the desired prosthesis, and therefore a large part of the autonomous system's weight. Similarly, the minimization of the mechanical work at the actuator output, without considering the peak of torque and velocity that can happen for example at low power, does not guarantee an optimal motor-gear selection both in terms of weight and efficiency. For these reasons, an optimal design approach should evaluate the dynamic effect of motor and transmission together with the action of the passive elements in order to optimize the final performance and mass of the powered prosthesis.

3 Our Approach

We propose an integrated design framework that can optimize concurrently the passive and active elements of the prosthesis in order to guide the actual design towards the achievement of the best global performance (i.e., active power, battery life, and total mass). The proposed design framework includes the dynamic effect of the motor and transmission, and allows the optimization of the passive-element configuration to obtain the best electrical efficiency and lowest total mass. A dedicated optimization is used for each specific passive element configuration and each specific motor-gear combination. Importantly, other than optimizing the energetic efficiency (i.e., electrical energy consumption per step), the proposed framework is intended to improve the global performance of the prosthesis, by evaluating the trade-off between energy efficiency, power density, and mass of each active and passive component, as a result of their interaction.

4 Current Results

The current simulation toolbox took as input the desired number of repetitions for each biomechanical task separately (i.e., walking steps, stair steps, and sit-to-stand iterations), as well as the maximum body weight to be supported by the prosthesis. Five different passive-element configurations were simulated (see Fig.1) *no spring*, *series spring*, *parallel spring*, *series and parallel spring*, and *series spring with infinitely variable transmission* (IVT) [10]. The output was provided as a separate data structure for each passive element configuration, containing the results of the dynamic simulation for each feasible motor-gear combination. Motors and gears parameters were taken from the Maxon Motor catalog 2012/13 (www.maxonmotorusa.org).

Fig.2 reports the simulation results for an ankle prosthesis supporting a 90 kg person walking at normal cadence (105.3 steps/s) for 10,000 steps. Input kinetics and kinematics were derived from

Winter's dataset [11]. Noteworthy, the passive-element configuration with the lowest total weight (series/parallel spring) was not the actuator that required the lowest mechanical work and electrical energy consumption (sIVT).

5 Best Possible Outcome

We will use the optimization framework to guide the design of a powered transfemoral prostheses tailored to the needs of the dysvascular amputee population. We expect to obtain a powered prosthesis that can provide the same power of an intact leg, similar inertia, lower mass and autonomy of 1 day of operations through using our proposed concurrent optimization approach.

Acknowledgement

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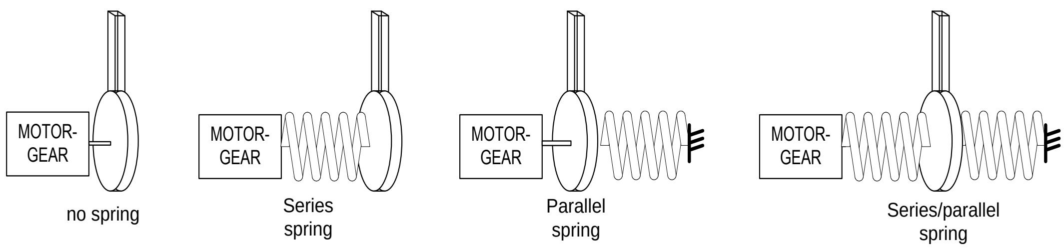

Fig1. Schematic representation of the passive-element configurations simulated by the optimization framework.

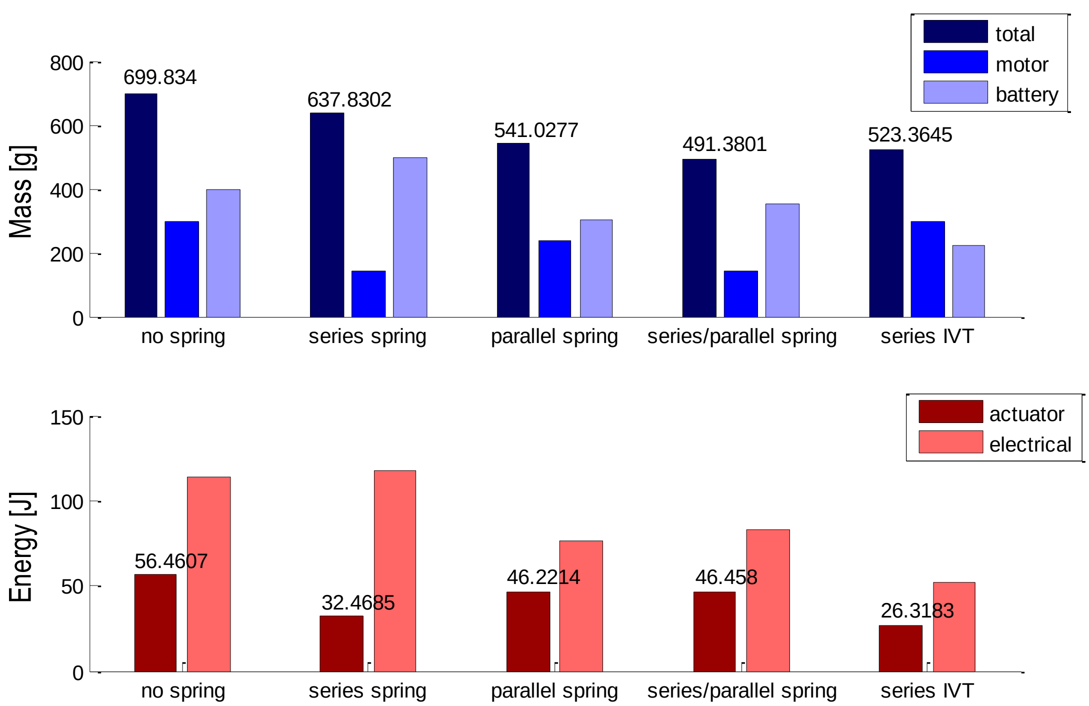

Fig. 2 Results of the optimization framework for a 90 Kg person walking at a cadence of 105.3 steps/min for 10,000 steps: The series/parallel configuration obtained the lowest mass (491 g), despite did not present the lowest mechanical work and electrical energy consumption. The series spring configuration had the highest electrical energy consumption but not the highest mechanical work.