Abstract

This research focused on designing, developing, and validating a novel partially-powered knee prosthesis, aiming to enhance the beneficial aspects of energetically passive microprocessor-controlled knees (MPKs). The enhancement involved integrating a compact electro-hydrostatic actuation unit with a controllable hydraulic valve. The design philosophy prioritized optimizing the prosthesis for swing-related activities, recognizing their vulnerability to external perturbations compared to load support phases. The proposed solution advanced prosthesis backdrivability and elevated versatility through a highly integrated actuation unit, facilitating integration by sharing the same motion transmission system for both active and passive locomotion activities. This resulted in augmented active power capabilities at the knee joint, contributing to a more responsive and adaptable prosthetic experience.

The doctoral work detailed the refinement of passivity enhancement, providing insights into the design and prototyping of the prosthesis. Supported by experimental evidence, the prototype's actuation unit underwent validation on a test bench, evaluating both active and passive functionalities. Subsequently, the prosthesis was evaluated considering a healthy subject equipped with an able-body adapter, during level ground walking and stair ascending. Comparative analysis against a commercial MPK showcased the distinct advantages of the developed prototype. With a weight of 2.15 kg, the prosthesis exhibited a markedly improved walking gait. The integration of the actuation unit enhanced the robustness of swing-related activities, contributing to increased toe clearance, reducing the likelihood of falling and scuffing. Experiments involving stair ascent highlighted the prototype's capability to perform a step-over step gait, showcasing remarkable versatility compared to traditional MPKs (i.e., minimal knee flexion is attained during stair ascent).

A functional analysis revealed that the prosthesis provided a minimum damping impedance of 2.6 Nms/rad at the knee joint and a maximum static friction of

approximately 1.4 $N \cdot m$. Under power generating conditions, particularly during a sinusoidal trajectory tracking task, the prototype could generate up to 52 W of power, achieving a peak flexion of up to 90° and a maximum rotational speed of 294 deg/s, highlighting the actuation unit's effectiveness in replicating the swing phase without necessitating hip effort. In conclusion, an energetic analysis, considering a 21.6 V battery pack with a capacity of 3350 $mA \cdot h$, revealed promising device autonomy. The prosthesis could provide significant autonomy at various speeds, ranging from 4260 to 9350 strides per battery charge, translating to a usage range from a maximum of 3 to a minimum of 1.5 days, based on the average number of steps per day performed by transfemoral amputees (TFAs) according to established literature.

In essence, this research suggested that supplementing an MPK prosthesis with a compact actuation unit could not only enhance the robustness of the swing phase during walking but also decrease the likelihood of scuffing, stumbling or even falling. Additionally, the innovative design enabled negotiating stair ascent in a step-over fashion, marking a significant advancement with respect to state-of-the-art MPK devices.