2020 I-RIM Conference
December 10-12, 2020, Rome, Italy (Virtual)
ISBN: 9788894580518
DOI:10.5281/zenodo.4781452

Highly Integrated Active Ankle-Prosthesis powered by an Optimized Lead-Screw Mechanism

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***Abstract*—Active ankle prostheses represent a field of growing interest for both industrial and academic researchers. The need of more functional devices, combined with the need of compact, light-weight and energy-efficient systems set a challenge to prosthesis designers. In this work, the authors try to give a solution to this problem by proposing a novel design of a lead-screw based active ankle prosthesis. The adopted approach aimed at optimizing the overall volume and weight of the actuating unit, while at the same time keeping the capability to satisfy both stance and swing phase requirements. A preliminary experimental evaluation has been carried out on a healthy subject to demonstrate the capabilities of the developed device in terms of stance braking torque and swing foot flexion.**

***Index Terms*—Ankle prosthesis, backdrivability, active, lead-screw**

I. Introduction

Lower-limb amputations represent a strong impairment to the quality of life and, to properly recover the bipedal locomotion, the amputee needs an adequate technical solution able to restore the physiological behavior of the sound limb.

Focusing on ankle prostheses, several solutions are available, both commercially and academically, ranging from fully-passive to fully-active devices [1]. Nevertheless, from a commercial point of view, the available devices present two main issues. Semi-active ankle prostheses are typically light-weight, but with limited functionality, guaranteeing either only active swing, e.g Proprio-foot® by $\ddot{O}ssur$, or controllable damping/braking, e.g. Merdium® by $Ottobock$. On the other hand, fully-active ankle prostheses provide greater functionality, but they are bulky, heavy and energy-consuming, e.g. BiOM® [2].

From an academic perspective, several research groups tried to address the design of active ankle prostheses capable of solving the presented issues. Some works focused on different actuating mechanism [3], while others analyzed the benefits of introducing elastic elements, e.g. variable series-elastic or clutched series-elastic, to enhance the performance of these devices [4], [5].

In this work, the authors propose a novel design approach of an active ankle prosthesis. The proposed solution, based on an optimized lead-screw actuation, tries to combine the strict constraints in terms of weight and size of an ankle prosthetic device with the biomechanical requirements of a physiological ankle. A state machine with a variable admittance controller is developed and tested on a healthy subject, to evaluate the device performances.

This work has been funded by INAIL/Rehab Technologies Laboratory in the Italian Institute of Technology.

II. Design

The design goal is to obtain a device that combines an active operation during the swing phase of the gait (characterized by minimal torque requirements) and an adaptive braking/damping operation during the stance phase (characterized by elevated braking torques).

In order to achieve this result, a lead-screw actuation has been selected. The lead-screw is mounted within an alternative four-bar linkage mechanism, showed in Figure 1, in order to convert the linear motion of the screw into rotary motion of the ankle joint. The screw is in turn actuated by a brushless DC motor unit coupled to an epicycloidal planetary gear.

In order to downsize the actuating unit as much as possible, the authors decided to adopt a design methodology focused on setting a target lead-screw efficiency of $\eta_{ls} \approx 50\%$. In this way, the lead-screw would be in a condition of quasi-backdrivability.

This means that, during the braking phases of the ankle gait, the body weight (acting as back-driving force on the lead-screw) would not enable the screw motion, thus avoiding the motor unit to take care of active braking. However, being so close to the backdrivability threshold will still allow the motor unit to modulate the braking phase, namely adjusting the lead-screw position and velocity, without consuming excessive amount of current to compensate for the resulting torque due to the external weight.

The lead-screw has been sized, e.g. screw diameter D and pitch p, following an iterative approach aimed to maintain the required efficiency (η_{ls}) while satisfying the geometrical constraints given by the prosthesis as well as the biomechanical requirements of the ankle.

Once the lead-screw was correctly sized, the design proceeded by selecting a suitable motor and gearbox to satisfy the system requirements. The resulting actuator is presented in Figure 1. The resulting prosthesis weights $0.814\,kg$ and occupies a volume of $92x61x160\,mm^3$, when using a foot of size 25 cat. 4.

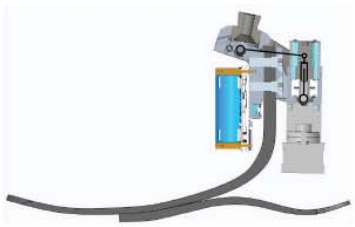

Fig. 1. The left image shows the resulting ankle prosthesis mountet on a high-profile ESAR foot. The right image presents a 2D-cross section of the assembly where it is possible to see the internal structure as well as a superimposed kinematic model.

The actuator is fitted on a high-profile energy storing and restitution (ESAR) prosthetic foot. Utilizing a high-profile foot guarantees an higher elasticity of the foot, thus producing a larger range of motion (ROM) and a higher energy storage that helps in downsizing the actuating unit. It is important to underline that such design doesn't guarantee an active propulsion of the patient during gait, which would otherwise have required a more powerful actuation.

III. Experimental Validation

The prosthesis has been equipped with digital Hall sensors to control the electrical motor, a custom torque-transducer and encoder to measure the ankle torque and to acquire the ankle angle and rotational speed. The resulting device has been tested on an healthy subject using an able-bodied adapter. From the control perspective, a variable admittance controller has been developed in order to reproduce different desired dynamical behavior. The admittance controller generates a reference signal that feeds the motor speed control loop.

The admittance control parameters, namely the desired stiffness, damping and inertia, have been tuned to reach the desired ankle motion and torque generation. Moreover, on top of the admittance controller, a state-machine has been designed to switch between stance and swing phase of the gait cycle and adapt the admittance control parameters accordingly.

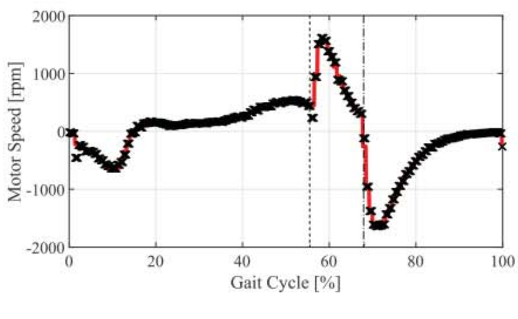

Fig. 2. Motor speed over a gait cycle: the red solid line represents the reference signal, while the black crosses show the measured one. Vertical dashed line represents the end of stance phase, while dot-dashed lined shows the end of swing dorsi-flexion.

Figure 2 shows the measured ankle angular speed trajectory compared to the reference signal generated by the admittance controller over a full gait cycle. It is observable that the device correctly tracks the desired trajectory with a root-mean squared error of $RMSE = \pm 38 rpm$ at the motor shaft.

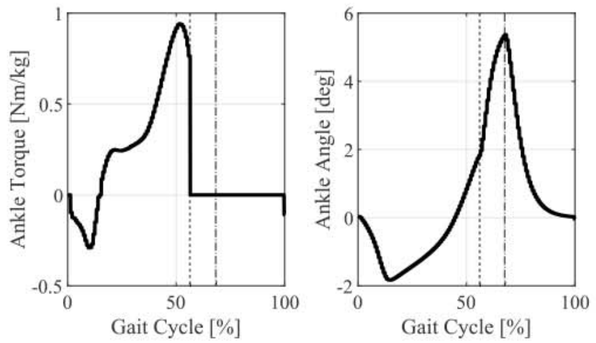

Fig. 3. The left chart shows the generated ankle torque, while right plot presents the obtained angular trajectory. Vertical dashed line represents the end of stance phase, while dot-dashed lined shows the end of swing dorsi-flexion.

Figure 3 presents, for the same gait cycle, the generated torque and measured ankle angular trajectory. The developed prosthesis is capable of generating sufficient braking torque with respect to a physiological sound limb one to support the stance phase, while at the same time offering a sufficient foot dorsi-flexion during swing phase to avoid tripping.

IV. Conclusion

The author presented the design of a highly-integrated active ankle prosthesis. The prosthetic device actuation is based on an optimized lead-screw mechanism that was strategically employed to downsize the actuating unit, while satisfying the required biomechanical specifications. In fact, the developed device demonstrated to be capable of providing the needed torque necessary for a correct motion during the stance phase. Moreover, it also showed its capability of mimicking the ankle angular motion during the swing phase. Future works will focus on performing clinical trials on different trans-tibial amputees to better assess the capabilities of the prosthesis.

References

[1] M. Windrich, M. Grimmer, O. Christ, S. Rinderknecht, and P. Beckerle, "Active lower limb prosthetics: a systematic review of design issues and solutions," *BioMedical Engineering OnLine*, vol. 15, no. 3, pp. 5–19, 2016.

[2] D. Hill and H. Herr, "Effects of a powered ankle-foot prosthesis on kinetic loading of the contralateral limb: A case series," in *IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*, 2013, pp. 1–6.

[3] B. J. Bergelin and P. A. Voglewede, "Design of an active ankle-foot prosthesis utilizing a four-bar mechanism," *Journal of Mechanical Design*, vol. 134, pp. 1–7, 2012.

[4] B. Convens, D. Dong, R. Furnemont, T. Verstraten, P. Cherelle, D. Lefeber, and B. Vanderborght, "Modelling, design and test-bench validation of a semi-active propulsive ankle prosthesis with a clutched series elastic actuator," *Robotics and Automation Letters*, vol. 4, no. 2, pp. 1823–1830, 2019.

[5] C. Everarts, B. Dehez, and R. Ronsse, "Variable stiffness actuator applied to an active ankle prosthesis: Principle, energy-efficiency, and control," in *Internation Conference on Intelligent Robots and Systems (IROS)*, Oct. 2012, pp. 323–328.