2 DoF robotic ankle exoskeleton

Michael Jacobson
Mechanical Engineering,
University of Illinois at Chicago
Chicago, USA
mjacob38@uic.edu

*Myunghee Kim**
Mechanical Engineering,
University of Illinois at Chicago
Chicago, USA
myheekim@uic.edu

***Abstract*—Ankle inversion-eversion control is an important method to restore balance in walking. We designed a tethered ankle-foot orthosis with a split-toe design to provide plantarflexion and inv/eversion torque with an off-board actuation approach. The orthosis is simple and lightweight, with a worn mass of 1.4 kg. Custom load cells coupled to the posterior end of the toes measure torque with 2Nm root mean squared (RMS) error. Benchtop tests demonstrated a step response rise time of 73 and 71 ms with 4.9% and 2.4% overshoot for peak torques of 140 Nm in plantarflexion and 30 Nm in in/eversion.**

Keywords—Ankle-Foot Orthosis, Balance, Rehabilitation

I. Introduction

Robotic orthoses has been used to enhance mobility [1]. Specifically, ankle-foot orthosis with plantarflexion assistance have demonstrated the capability to restore normal ankle kinematics and reduce metabolic cost. Further examination from previous robotic prosthesis addresses the importance of active inversion-eversion and plantarflexion assistance [2, 3]. With this understanding of in/eversion significance, ankle exoskeletons have begun to explore the benefits of an added degree of freedom which includes active inversion-eversion assistance [3] with maximum torque 18 Nm and worn weight of 2.14 kg. A device with a wide range of torque assistance may provide greater assistance benefits with an alternative approach to incorporating ankle in/eversion.

II. Methods

A. Mechanism

We designed a two degree of freedom ankle–foot orthosis end-effector with active plantarflexion and in/eversion utilizing a tethered emulator system (Fig.1). Off-board actuator transmits mechanical power via two Bowden cable tethers attached to the orthosis. Orthosis end-effector dimensions were based on the average U.S. male foot size; 0.3 m in length, 0.12 m in width, and 0.08 m in height. Toe length, from axis of rotation to the anterior vertex, is 0.10 m. Ankle range of motion is -80° to 50° in plantarflexion and -20° to 20° in inversion-eversion, with respect to the neutral stance in which the toes are flat on the floor and the sagittal plates are 90 degrees from edge-to floor. The orthosis generates torque and movement in both plantarflexion and inversion-eversion directions using two independent toes. Plantarflexion occurs when both toes rotate in the same direction, and in/eversion occurs when they rotate in opposite directions. We define plantarflexion angle as the average of the toe angles and in/eversion angle as the difference between the two toe angles multiplied by the ratio of toe length to half the foot width. Plantarflexion torque was defined as the sum of the lateral and medial toe torques while inversion torque was defined as the difference between the lateral and medial toe torques multiplied by the same constant.

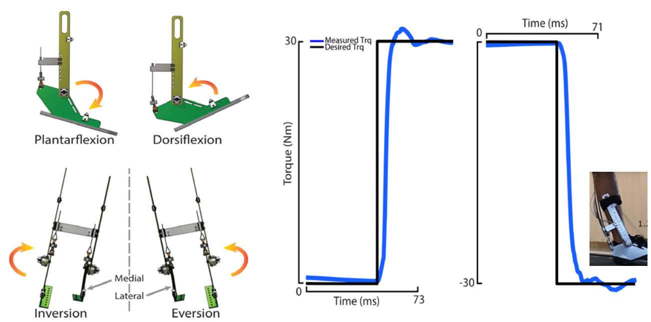

Fig. 1. 2DoF robotic ankle exoskeleton with plantarflexion and in/eversion (left) Step response graph for inversion and eversion benchtop test (right).

B. Benchtop Testing

Calibration and step response tests were conducted by fixing the spur of the device to a rigid test fixture with the bottom of the sole facing up. To calibrate the ankle torque sensing, we loaded, and de-loaded a series of 4.5kg weights, and determined a linear relationship between load cell voltage and torque. Step response tests were completed to measure plantarflexion (0-140 Nm) and inv-eversion (-30 Nm to 30 Nm) step response to determine maximum rise and fall times.

III. Results and Discussion

Torque calibration tests display an RMS error of approximately 2 Nm for each toe. The plantarflexion step response showed a steady-state error of less than 4% with rise time 80 ms. Inv/eversion step repsonse presented rise times of approximately 73 ms and 71 ms, with 4.9% and 2.4% overshoot, respectively. This ankle-foot orthosis has been successfully used to personalize assistance during squatting and walking, which resulted in 20% physical effort reduction. This performance suggests that a lightweight tethered end effector with two degrees of assistance can be used to test controllers and balance-related features in orthosis and therefore be used in rehabilitative or occupational activities.

[1] Raab, K., et. al., (2016). Effects of training with the ReWalk exoskeleton on quality of life in incomplete spinal cord injury: a single case study. *Spinal Cord Series and Cases*, *2*(1), 1–3.

[2] Kim, M., et. al, (2018). An ankle--foot prosthesis emulator with control of plantarflexion and inversion--eversion torque. TRO.

[3] Kim, M., & Collins, S. H. (2017). Step-to-step ankle inversion/eversion torque modulation can reduce effort associated with balance. Frontiers in neurorobotics

[4] Choi, H. S., & Baek, Y. S. (2020). Effects of the degree of freedom and assistance characteristics of powered ankle-foot orthoses on gait stability. *PLoS ONE*,