Portable Pneumatically-Powered Ankle-Foot Orthosis

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1 Introduction

The goal of this work is to address challenges with developing and utilizing mobile powered orthotic devices or exoskeletons, especially those that depend on miniature pneumatic power systems. We present an ongoing research testbed to explore hardware and software solutions related to effective, efficient control and operation of such devices. The testbed platform is a pneumatically-powered ankle-foot orthosis that can provide bidirectional (dorsiflexor, plantarflexor) torque. A mobile pneumatic power source can be used to examine issues related to providing gait assistance in a variety of environments beyond walking on a treadmill or confined level-ground space. We refer to this platform as the Portable Powered Ankle-Foot Orthosis (PPAFO) (Fig. 1) [1].

Specific systems engineering areas addressed by the PPAFO have been actuation timing control for gait assistance [2], gait mode recognition control when traversing different environments (level ground, stairs, ramps) [3], and design efficiency opportunities to extend runtime of a pneumatically powered system [4]. We have conducted preliminary studies to assess the effects of applied ankle torque for gait assistance (with able-bodied and disabled groups) [5,6] and gait initiation (with persons with Parkinson's disease) [7,8].

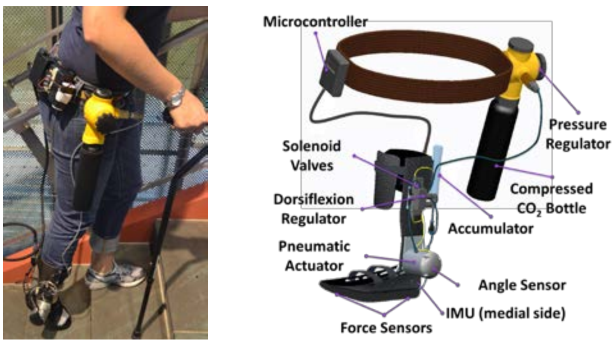

Fig. 1. Portable Powered Ankle-Foot Orthosis (PPAFO)

2 PPAFO Hardware

Due to current technology lags in compact, lightweight, powerful, and energy dense actuation and power sources, the orthosis was constructed using off-the-shelf (OTS) pneumatic components to demonstrate device feasibility and to allow beginning explorations into the challenges of mobile and/or wearable robotic devices. The PPAFO can be pneumatically powered by a canister and pressure regulator with compressed carbon dioxide when portability is required (JacPac J-6901-9; Supplierpipeline, Inc.; Waterloo, Ontario, Canada), or tethered to a pneumatic generator or central supply line when examined in a laboratory setting. Two device generations have been tested.

The current embodiment used a bidirectional, dual-vane, rotary pneumatic actuator with 90° ROM capacity to create dorsiflexor or plantarflexor torque (PRN30D-90-45; Parker Hannifin, Cleveland, OH). Due to pressure limitations of multiple components, the maximum operational pressure can be 150 psig. As a consequence of this operating pressure, the desire to minimize size and weight of the orthosis at the ankle, and achieve a range of motion up to 55º (to accommodate full range of passive motion), the available compact OTS actuators used in the PPAFO can only achieve a maximum torque of 15 Nm. Due to this low peak plantarflexor torque and no need to track a torque or joint angle profile, we chose to use solenoid valves to control ankle joint actuation (VUVG 5V; Festo Corp-US; Hauppauge, NY). These valves are smaller, lighter and more efficient than commercially available pneumatic proportional valves. A second pressure regulator mounted on the PPAFO (LRMA-QS-4; Festo Corp-US, Hauppauge, NY) modulated the much smaller dorsiflexor torque needed to compensate for the inertia of the foot during swing (e.g., 3 Nm).

Foot and tibial pieces were constructed from preimpregnated carbon-composite laminate materials. In the current embodiment, the tibial shell has no medial strut. Bilateral shells were modeled to fit three tibial sizes (small, medium and large adult male) and four foot sizes (US men's 4 to 14). A foam sole was cemented to the plantar surface of the foot shell. Foam padding was used to align the orthosis joint with the lateral malleolus and fit of the foot and tibial pieces.

Control of the PPAFO valves and collection of sensor data were accomplished with a microcontroller (MSP430G2553; Texas Instruments, Dallas, TX) sampled at 120 Hz. A Hall effect sensor (model KMA199E; NXP Semiconductors, San Jose, CA) measured ankle angle. Heel and toe contact were detected from force sensitive resistors (403, 2" square; Interlink Electronics Inc., Camarillo, CA) embedded under the heel and ball of the foot.

The total system weight was 3.65 kg; orthosis alone (1.83 kg), remainder of weight at waist on belt (microcontroller and CO_2 power supply). Current work includes designing new pneumatic actuation systems, including the use of soft robotic actuators that are capable of generating larger magnitudes of torque while considering compact size and weight.

3 Actuation Timing Control for Gait Assistance

Throughout the development of the PPAFO, progressively more complex actuation timing control schemes have been utilized in an effort to better accommodate more complicated gait patterns of different patient populations.

Two main control schemes have been implemented: Direct Event and State Estimation. The finite state Direct Event (DE) controller [1] used the heel and toe force sensors to detect the event boundaries of four regions (initial contact, loading response, forward, and limb advancement during swing). State estimation (SE) [2] used real-time force sensor data to estimate the state of the actual system as compared to a predetermined model that represents boundaries for the four regions. For our SE controller, the four regions were defined (in terms of percent gait cycle) as Initial contact: 0 to 7; Loading response: 7 to 48; Forward propulsion: 48 to 62; Limb advancement: 62 to 100, based on gait cycle timings adapted from [9]. Two SE algorithms have been used. The simplest is Fractional Time (FT) which assumes that the estimated state increases linearly with time elapse from the last heel strike event. A Modified Fractional Time (MFT) state estimator was defined with eight events during a gait cycle and three sensors (heel force, toe force, ankle angle) to estimate the percentage of gait cycle. MFT will adapt faster as the controller updates the estimated state eight times per cycle. However, the MFT-SE controller must be initially trained and adapted to an individual's gait pattern using the appropriate sensor signals. FT-SE does not need training except for determining the heel sensor threshold, which did not tend to change much between participants. Currently, we are examining the used of Bayesian regularized artificial neural networks for estimating state.

4 Gait Mode Recognition and Control

To address walking through different environments (level ground, stairs, ramps), we examined recognition and control for different gait modes [3]. It was determined that only stair or ramp descent required a different control scheme than level ground or stair/ramp ascent (plantarflexion vs. dorsiflexion during swing, respectively). Foot position and orientation were determined using a 6 DOF IMU (MTi-28A53G35; XSens Technologies, Enschede, The Netherlands), heel sensor and toe sensor. Orientation determined foot pitch angle using the gyroscopes in the IMU. Vertical foot position (elevation) was determined from the IMU accelerometer and force sensors. Integration of the acceleration data can provide velocity and position; however, these calculated values will drift over time. To compensate for the drift in velocity, the velocity signal needed to be recalibrated. Heel contact provided a useful instant when vertical velocity could be re-zeroed. This technique resulted in average success rates for identifying level ground, stairs, or ramps of 97-99%. Although having a high identification success rate, the use of a single IMU still resulted in a one-step delay in control actuation of the PPAFO. Current work is addressing this delay.

5 Efficiency Analyses for Improved Runtime

The development of mobile devices needs to consider how to create more energy-dense power sources or design devices that are more efficient with the energy required. With the increased interest in soft robotics, which are reliant on pneumatic power sources, examining pneumatic energy sources and extending runtime are critical challenges to consider. We examined the effect on fuel efficiency and runtime of different control algorithms, direct event vs. fractional time state estimation (DE, SE) and use of an exhaust gas recycling scheme with either controller (DER, SER) [4]. The recycling scheme involved capturing the exhaust gas from the higher pressure plantarflexion actuation into a custom strain-energy accumulator and then using the captured gas to power the lower pressure dorsiflexion actuation. Thus, the power source was only sampled once, during the plantarflexion actuation. The state estimation with recycling (SER) was the best of the controllers due to reduced fuel consumption and consistent controller scheme leading to reliable work output. Runtime can be nearly doubled from 27 to 47 minutes.

5 Functional Evaluation

The PPAFO testbed is being used to understand the effect of powered ankle joint actuation on able-bodied gait and impaired gait. The impact of the bidirectional torque on these populations will be useful in creating guidelines for future assistive device development. Early data demonstrated improved gait functionality (e.g., increased power, ground reaction forces, cycle and stance times, and improved ankle joint positioning) from two subjects with bilateral impairments to the lower legs [1,5]. An ongoing study on persons with multiple sclerosis is comparing the impact of an externally applied bidirectional ankle torque via the PPAFO to their physician-prescribed passive AFO. Preliminary results suggest that the PPAFO encouraged shorter strides and slower strides than a custom AFO. In another ongoing study, we are investigating the utility of a wearable device that provides modest mechanical assistance via dorsiflexor and plantarflexor torques to facilitate gait initiation, especially for persons with Parkinson's disease who have trouble initiating the first step. Mechanical assistance provided by the PPAFO was compared to baseline self-initiated and acoustic-cued stepping conditions. Results suggest that mechanical assistance could improve force production and lateral weight shift during the anticipatory postural adjustments (APAs) observed during gait initiation.

Acknowledgements: Thanks to K. Alex Shorter, Yifan David Li, Geza Kogler, Morgan Boes, Matt Petrucci, and Mazharul Islam, and the NSF Engineering Research Center for Compact and Efficient Fluid Power (#0540834).

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