Fuel Efficiency of a Portable Powered Ankle-Foot Orthosis

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Abstract*— A Portable Powered Ankle-Foot Orthosis (PPAFO) has been designed for gait assistance. The PPAFO can supply assistive torque at the ankle joint in plantarflexion and dorsiflexion using a bidirectional pneumatic actuator. Two control schemes have been developed to regulate timings of the assistive torques during different phases in the gait cycle. The Direct Event (DE) controller uses heel and toe force sensors to detect the start and end of key phases using specific events (e.g., heel strike and toe-off). The State Estimation (SE) controller finds the least-square-error between real-time sensor data and a reference model from training data to estimate the gait state and to detect phases based on this estimate. A pneumatic recycling scheme for improved fuel efficiency was also implemented. This scheme regenerates energy from plantarflexion exhaust gas to power dorsiflexion actuation. The objective of this study was to assess the fuel efficiency of these two controllers and pneumatic recycling scheme, as measured by fuel consumption and work output. Data were collected from 3 minute walking trials with the PPAFO by five healthy young control subjects. The SE with recycling (SER) scheme had an average fuel savings of 25% compared to the SE control scheme, and 24% compared to the DE controller. The SER controller allowed for comparable net work output to the SE controller which both did more net work than the DE controller. These observations can be applicable to other portable fluid-powered orthotics, prosthetics, and robotics in terms of potential impact of controller choice and energy regeneration on fuel consumption.

Keywords*— *ankle-foot orthosis, gait assistance, powered orthosis, efficiency, exoskeleton, pneumatic recycling, regenerative, fluid power

I. INTRODUCTION

Ankle-foot orthoses are important in improving gait function of people with lower leg neuromuscular dysfunction and muscle weakness. An ankle-foot orthosis (AFO) is an external device worn on the lower leg and foot that provides mechanical assistance at the ankle joint. Current commercially-available AFOs for daily gait assistance are passive or semi-active devices that provide joint stability and motion control; however, there are no untethered AFOs that also provide active assistance throughout all phases of the gait cycle including late stance and propulsion [2]. Powered AFO systems that provide both dorsiflexor and plantarflexor torque assistance have recently been developed for laboratory and clinical use, but these systems require an electric or fluid power tether to a large external power source e.g.[3, 4]

Recently, an untethered powered AFO system has been developed - the Portable Powered Ankle-Foot Orthosis (PPAFO) [5]. This system uses fluid power in the form of pneumatics to supply dorsiflexor or plantarflexor torque at the ankle via a pneumatic rotary actuator mounted at the ankle (Fig. 1). One of the current limitations of this pneumatically-powered AFO system is the portable usage time due to the fixed amount of power available in a compressed carbon dioxide (CO_2) tank that is used as the portable power source (e.g., with a 20 oz. tank run time is around 20-30 minutes or 1,000 steps). For the PPAFO, extending the continuous operation time to an hour, for example, could allow operation for a daily rehabilitation intervention session. In order to improve the run time without increasing the size of the power source, a theoretical systematic overall efficiency analysis was conducted and solutions to enhance efficiency were proposed [6].

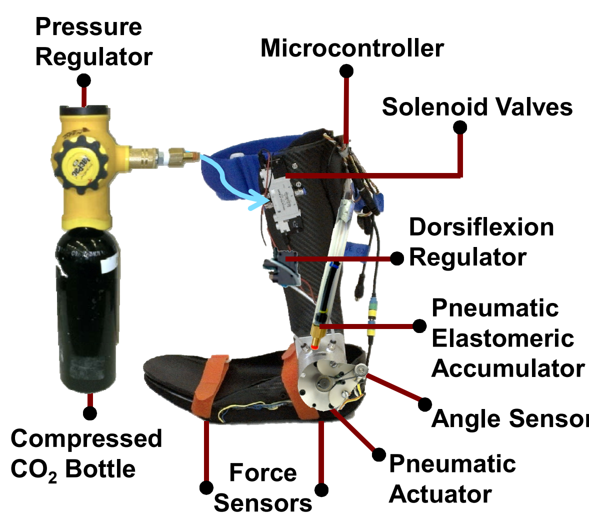


Fig. 1: The portable powered ankle-foot orthosis (PPAFO) system.

Throughout the development of the PPAFO, different control schemes have been utilized [7]. A given control scheme determines the timing of the pneumatic system in regards to cues from sensors on the PPAFO (Fig. 1). Two control schemes that have been implemented on the PPAFO are the Direct Event (DE) and the State Estimation (SE) control schemes [5, 7]. The DE controller is quite simple to implement and uses the force sensors at the heel and ball of foot as event indicators and responds in real time to the signal it receives [5]. The SE controller requires more computational cost. It uses the force sensor signals and angular position signal from a potentiometer to inform the timings of a predetermined gait cycle model. As the model of the gait cycle receives information from the sensors, it updates the timing of the gait cycle, while continuing to give assistance at prescribed significant time points in the gait cycle [7]. The SE controller was found to perform better at restoring normative gait kinematics, especially for people with impaired gait patterns that were not able to properly trigger the DE controller [7].

In a previous theoretical efficiency study, we proposed to change the pneumatic circuit to include a novel pneumatic energy regeneration strategy to improve system efficiency and reduce fuel consumption [6]. The recycling scheme suggests capturing the exhaust gas from one part of the actuation cycle (plantarflexion) and using (or regenerating) it to drive actuation in the opposite direction (dorsiflexion). This recycling scheme would result in the CO_2 bottle to be accessed for fuel once per gait cycle to power plantarflexion, instead of twice per cycle to power both plantarflexion and dorsiflexion as in the original design. Theoretical calculations predict that the fuel savings could be upwards of 30% [6].

There were two objectives for the current study. The first was to physically implement the recycling scheme onto the PPAFO pneumatic circuit. The second was to compare the two control schemes and two pneumatic circuits and assess their effects on fuel efficiency. Change in fuel efficiency of the PPAFO was evaluated by examining fuel consumption and net work output during walking. It was expected that the SE controller would allow the PPAFO to do more net work than the DE controller, as it has more information on the gait states and therefore is better timed to give assistance that is in sync with the natural motion of the user. Implementing the recycling scheme with state estimation (SER) should produce the same net work output as the non-recycling state estimation scheme (SE), but with notably less fuel consumption. This fuel efficiency study, which compares on the effect of controller modes and a regenerative power scheme on fuel consumption and net work output, has general application to the field of portable fluid power-based orthoses, prostheses, and robots, which will rely on efficient operation for extended use.

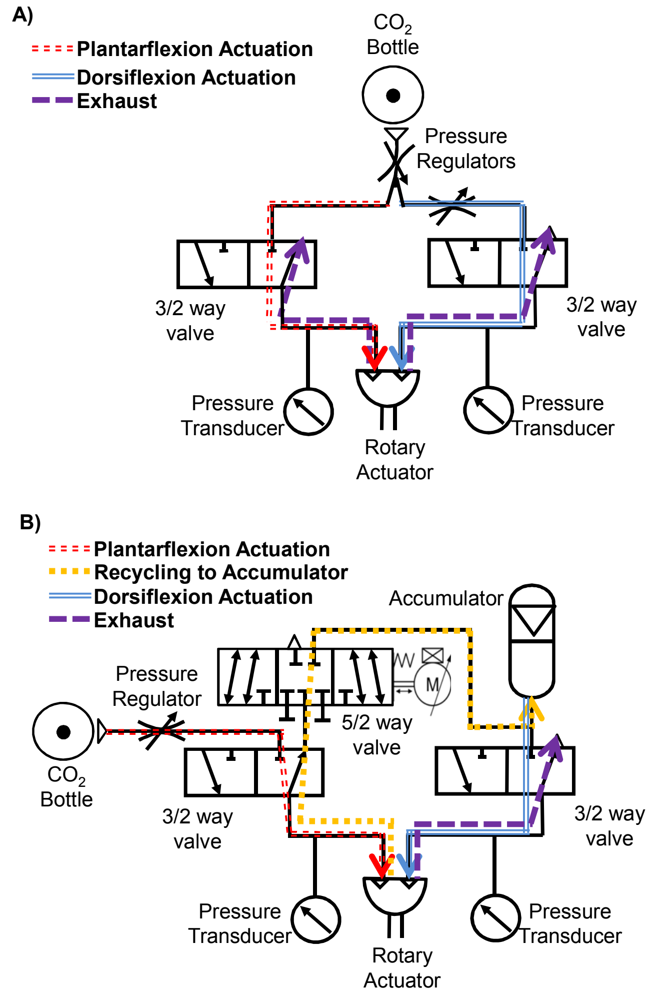


Fig. 2: PPAFO pneumatic circuits. A) Original pneumatic circuit supplying both plantarflexion and dorsiflexion from the CO_2 tank. B) Pneumatic circuit using an accumulator and three solenoid valves to recycle exhaust gas from plantarflexion actuation to power dorsiflexion. The legends indicate the pneumatic flow in the valve sequences of the cycle.

II. Methods

First, the recycling scheme will be described, where an accumulator is included to collect the exhaust from the high-pressure plantarflexion actuation, and power the low-pressure dorsiflexion actuation. Then, the two controller modes will be described in detail. Finally, a walking experiment to assess the effect of the control and recycling schemes will be presented.

A. Reycling Scheme

In our previous studies, a recycling scheme was proposed [6] to improve system efficiency by reducing fuel consumption. In the original pneumatic circuit, two solenoid valves (VUVG 5V; Festo Corp-US, Hauppauge, NY) were used to control a rotary actuator (PRN30D-90-45, Parker Hannifin, Cleveland, OH) that can be actuated in dorsiflexion and plantarflexion directions (Figs. 1 + 2A).

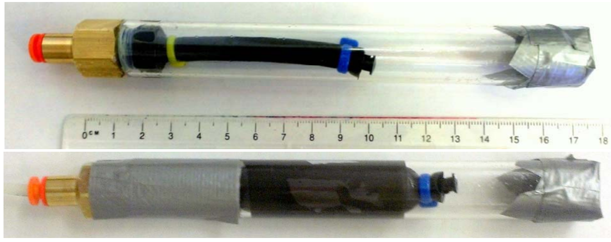


Fig. 3: Custom pneumatic elastomeric accumulator (PEA) assembled from off-the-shelf components. A polycarbonate sheath constrains the expansion of the elastomer when filled with compressed gas.

To implement this recycling scheme, an additional solenoid valve (VUVG 5V; Festo Corp-US, Hauppauge, NY) and custom accumulator were added into the pneumatic system (Fig. 2B).

A four-phase procedure (Fig. 2B) allowed the compressed exhaust air from each plantarflexor actuation to be stored in the accumulator and released later to power the consecutive dorsiflexion. This approach guaranteed the same level of net work output in both directions, while reducing fuel consumption.

The accumulator was a custom-constructed elastomeric accumulator (Fig. 3). The pneumatic elastomeric accumulator (PEA) concept was based on previous work completed in hydraulics where fluid power energy was stored in an elastomer that was then able to return the stored energy to the system [8]. As the compressed gas enters the accumulator, the elastomer is allowed to expand within the sheath constraint. When the accumulator powers dorsiflexion, the strain energy stored in the expanded elastomer reenters the system along with the stored compressed gas, as the elastomer returns to its original relaxed state. The PEA was assembled from off-the-shelf pneumatic fittings, latex tubing, and a cylindrical polycarbonate sheath.

B. Different control modes for PPAFO

1) Direct Event Control Mode

The finite state Direct Event (DE) controller [5] is a common and reliable approach with the benefit of simple implementation [9-12]. This approach checks to see if sensor measurements exceed given thresholds, thus detecting specific gait events. The two force sensitive resistors (403, 2" square; Interlink Electronics Inc., Camarillo, CA, USA) embedded under the heel and ball of the foot in the sole of the PPAFO were used to determine gait state. Each on-and-off combination of the two sensors was considered one of four gait events, which were associated with different gait phases (Table I). Heuristically-tuned thresholds were used to determine the "on" configuration for the two force sensors. The controller was used to switch the actuation direction (or turn it off) based on the combination of the two force sensors (Table I). During initial contact, only the heel sensor was compressed and dorsiflexor assistance was provided to slow the forefoot descent and prevent foot slap. During the loading response, when both sensors were compressed, there was no actuation to allow for free range of motion. When only the toe sensor was compressed, plantarflexor actuation was used to assist forward propulsion. The swing phase was identified when both sensors were uncompressed, and dorsiflexor actuation was used to hold the toes up, preventing foot drop.

TABLE I. DIRECET EVENT CONTROLLER SCHEME

Phase	Heel	Toe	Torque Direction
1. Initial Contact	ON	OFF	Dorsiflexor
2. Loading Response	ON	ON	None
3. Forward Propulsion	OFF	ON	Plantarflexor
4. Limb Advancement	OFF	OFF	Dorsiflexor

TABLE II: STATE ESTIMATION CONTROLLER SCHEME WITH RECYCLING

Phase	% gait cycle	Torque Direction
1. Initial Contact	0-7	Dorsiflexor
2. Loading Response	7-48	None
3. Forward Propulsion	48-62	Plantarflexor
4. Limb Advancement	62-67	None – Charging[a]
	67-100	Dorsiflexor

[a.] During SE without recycling, dorsiflexor torque starts at 62% of the gait cycle as there is no need for a charging phase

[b.] Gait cycle timings adapted from Perry [1]

2) State Estimation Control Mode

The State Estimation (SE) control mode algorithm uses real-time sensor data and through least-squares regression compares the signal values to a pre-computed training model to determine the current state [7]. The sensor data come from the two force sensors and an angle sensing potentiometer (53 Series, Honeywell, Golden Valley, CA). Similar to DE control, the SE controller will provide actuation during four gait phases: (1) initial contact, (2) loading response, (3) forward propulsion, and (4) limb advancement.

The state estimators were based on a pre-computed model from previously measured gait training data that tells what sensor measurements to expect at a given state. The training data were also used to create models for each of the sensor measurement during the gait cycles [7]. The results of this model dictate the timing of the torque assistance from the SE controller (Table II).

C. Controller and Data Collection

An embedded micro-controller (MCU) (MSP430G2553, Texas Instruments, Dallas, TX) was used to control the PPAFO valves and collect sensor data. The MCU acquired the analog signals from the heel, toe and angle sensors, and pressure transducers (AST4000A00150P3B1000, 150 psig and AST4000A00100P3B0000, 100 psig, American Sensor Technologies, Inc, Mount Olive, NJ) that were used to measure the compressed CO_2 pressure on both sides of the actuator. Wireless communication between the MCU and a desktop computer was established via a pair of XBee wireless radios (XBee Pro: Frequency: 900 MHz, RF Data Rate: 156 Kbps Digi International Inc., Minnetonka, MN). A 5th order Butterworth low pass filter with a cut-off frequency of 8 Hz was applied to all incoming sensor data. All data collection and data processing were completed with MATLAB (v 7.13.0.564, the Mathworks, Waltham, MA).

D. Experimental Protocol

1) Subjects

In this study, five subjects participated. All subjects were healthy young adult males (age 20-29 years, height 177.8 ± 4 cm, weight 76.7 ± 9.7 kg) having no neurological, gait, or postural disorders. Informed consent was given by all subjects and the university institutional review board approved the study.

2) Experimental Procedure

Each subject was tested under three conditions, one for each of the control modes: Direct Event control mode without recycling (DE), State Estimation control mode without recycling (SE), and State Estimation control mode with recycling via elastomeric accumulator (SER). A DE control mode with recycling was not included, as it has previously been established that the SE controller is more robust and accurate when providing timed assistance to both healthy controls and impaired subjects [7]. Each subject walked at his comfortable speed on a treadmill (Fully Instrumented Treadmill, TM07, Bertec, Columbus, OH) (mean = 0.90 ± 0.04 m/s) for 3 minutes per trial of each condition. Two trials were performed for each condition. Comfortable walking speeds were determined by allowing each subject to adjust walking speed before the testing began.

E. Fuel Consumption Calculation

The CO_2 bottle mass was recorded before and after each trial to determine overall CO_2 fuel consumption for a trial and between test conditions. The fuel consumption was divided by the number of steps taken in each trial to obtain a metric of fuel consumption per step. Four compressed carbon dioxide bottles (JacPac J-6901-99, 20 oz capacity; Grainger, Inc [Burr Ridge, IL]) were rotated through the trials as the fuel sources in this study. Compressed CO_2 has a thermal cooling nature such that the bottle cools even over short periods of continual use. This cooling can lead to subsequent pressure decrease over time. Therefore the CO_2 bottles were allowed to reach room temperature between trials.

F. Net Work Output Calculation

The net work output by the PPAFO system was computed for each trial by examining the change in volume and pressure in the actuator of the PPAFO. The change in volume of CO_2 in the actuator was calculated from the ankle angle data as determined from the potentiometer per the following:

$$Volume = k\,\theta \quad (1)$$

where k = 0.38 cm^3/ degree. This coefficient was determined from knowledge that the total volume of the actuator was 34 cm^3, and the range of motion was 90 degrees.

Pressure readings from the pressure transducers were used to calculate the pressure difference across the actuator. With these two quantities, net work output of the system during each sample time, $\Delta t = 0.004$s, as a function of gait cycle was calculated as

$$\Delta W = \left(P_{plantarflexion} - P_{dorsiflexion}\right) \times \Delta V \quad (2)$$

The net work output per step was calculated as the summation of the work output over an entire gait cycle

$$W = \sum_{each\ gait\ cycle} \Delta W \quad (3)$$

The net work, *W*, represents the total work output of the PPAFO.

G. Statistical calculations

Controller conditions for fuel consumption per step, net work output per step, and net work output per fuel, averaged over all participants were analyzed with repeated-measures ANOVA tests (SPSS 20, IBM, New York). Post-hoc analysis using Tukey's HSD tests were used to determine specific condition differences. Significance was set at $p<0.05$.

III. RESULTS

A. Fuel consumption

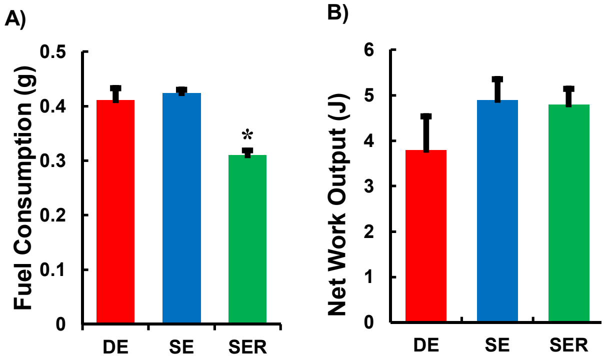
The first comparison of interest was to determine whether the two control schemes (DE and SE) resulted in different amounts of fuel consumption. Fuel consumption was measured for the entire 3 minute trial and then determined per step based on the number of steps taken in the trial (Table III). Each subject took approximately 145 steps in the 3 minute trials. The average amount of fuel per step with the DE controller was 0.41± 0.02g (mean ± S.E.). The average amount of fuel used per step with the SE controller was 0.42± 0.01g (mean ± S.E.).

The SER system was designed to save fuel by implementing a pneumatic recycling scheme. The average amount of fuel used per step with SER is 0.31± 0.02g (mean ± S.E.), which was 25.4% less fuel compared to the fuel consumption of SE.

Statistical analysis indicated that the SER condition used significantly less fuel than either the SE or DE controllers,

TABLE III. FUEL CONSUMPTION IN 3 MINUTES OF PPAFO USE

	Direct Event	**State Estimation**	**State Estimation with Recycling**
Fuel Consumption over 3 minutes (mean ± S.E.)	58.8 ±2.7 g	60.6 ±1.8 g	45.2±1.7 g



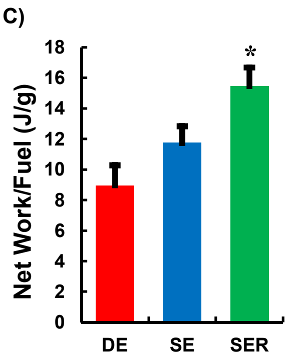


Fig. 4.: Results for energy efficiency analysis. Bar graphs display group means with error bars of standard error. A). Fuel consumption per step of PPAFO. B). Net work output per step of PPAFO. C). Net work per fuel consumption of PPAFO usage.

while the two basic controllers did not use significantly different amounts of fuel per step ($p < 0.001$, Fig. 4A).

B. Net Work Output

The amount of net work output of the PPAFO indicates the amount of assistance given to the participant. A larger amount of net work output implies that the timing of the controller is better aligned to assist with the natural motion of the participant, allowing the PPAFO to give more assistance with a broader range of motion at the ankle (Fig. 5). There was no significant difference in the amount of net work output between any of the three controllers (DE, SE, and SER; 3.8 ± 0.7J, 5.0±0.5J, and 4.8±0.3J (mean ± S.E.), respectively; p = 0.151, Fig. 4B).

To gain a better overall picture of the fuel efficiency of the system based on controller, the net work per gram of fuel was calculated (Fig. 4C). , The SER fuel efficiency was significantly greater than both the SE and DE controllers (DE: 9.0 ± 1.3J/g, SE: 11.7±1.1 J/g, SER: 15.5±1.2 J/g (mean ± S.E.); p<0.001).

IV. DISCUSSION

The objectives of both implementing the recycling scheme and comparing the net work output of the two controllers and pneumatic circuits were achieved. When the state estimation controller included the recycling scheme, a fuel reduction of 25.4% was observed (SER: 0.31± 0.02g, SE: 0.42± 0.01g, mean ± S.E.). While the DE controller is easier to implement, it is less robust and can result in greater misfiring of the actuators especially when the user has impaired gait that cause incorrect or missed triggering of the sensor. The SE controller provides improved estimation of the gait phases, allowing for better timing of PPAFO actuation assistance [7]. The differences described in the controllers are likely what allowed the SE controller to do slightly more net work than the DE controller. More importantly, the SE controller has less variance in the amount of net work output and fuel consumed across all five subjects suggesting that it is a more consistent controller (Fig. 5B). Inclusion of recycling (SER) allows for the PPAFO to both have improved actuation and lower fuel consumption.

There are notable limitations of this analysis. The first is that we did not include an unimpaired gait population. Since persons with impaired gait are the target users for the PPAFO, it will become important to determine the operational limitations for those populations. The altered gait mechanics of a biomechanically impaired person will likely impact the fuel consumption and net work output of the two control schemes. Although regardless of population, it is understood that the recycling scheme will always use less fuel than the non-recycling scheme. The small sample size is also a limitation in generalizing the results to a larger population of PPAFO users. The small sample size may not have captured the diversity of gait kinematics even within non-impaired persons.

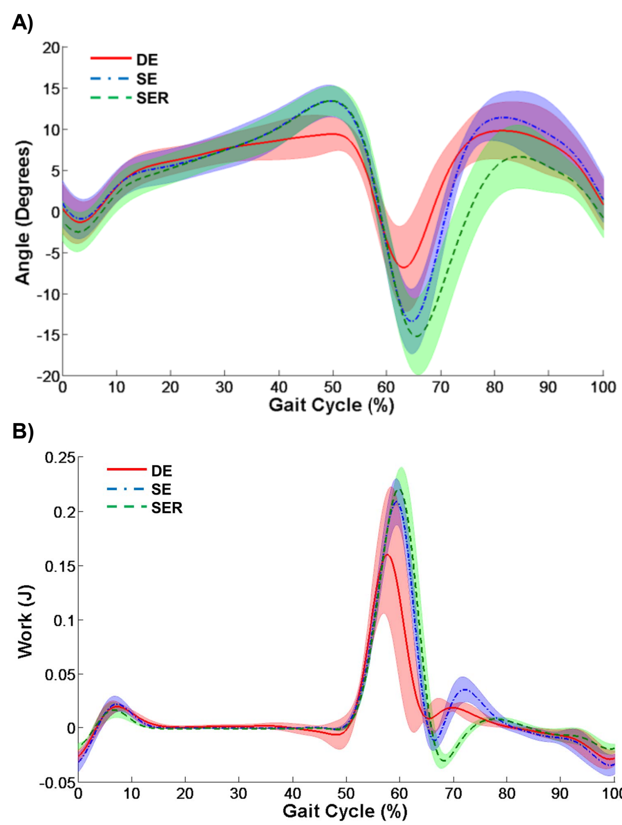


Fig. 5: Ankle angle (A) and net work output (B) as functions of percent gait cycle. Dorsiflexion is positive and plantarflexion is negative. Lines indicate group means, shaded areas indicate standard deviation.

V. CONCLUSIONS

The differences between control schemes in net work output and fuel consumption can be attributed to the actuation timing of the PPAFO. State estimation control with exhaust recycling is an exciting breakthrough in improving the total fuel efficiency and robustness of the system. The regenerative nature of the SER system allows for substantial fuel savings while maintaining the benefit of improved actuation timing based on estimated gait phases from the SE controller. By using less fuel than the DE and SE controllers without recycling, the recycling configuration should be able to successfully extend the total run time of the fuel source. The results of this fuel efficiency study illustrate how choice of control strategy can impact fuel usage, and how a regenerative exhaust-recycling scheme can reduce fuel usage. Developers of other portable fluid powered orthoses, prostheses, and robots should be cognizant of the potential impact of controller choice on fuel consumption and the benefits of a regenerative circuit.

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