Trunk postural tracking of assistive soft pneumatic actuator belt

Matthew A. Robertson[1], Hamed Sadeghi[2], Juan Manuel Florez Marin[3], Jamie Paik[4]

[1, 2, 3, 4] École polytechnique fédérale de Lausanne (EPFL)

[4] jamie.paik@epfl.ch

Summary

Fiber-reinforced Soft Pneumatic Actuators (SPAs) are found in mobile robots, assistive wearable devices, and rehabilitative technologies. Being intrinsically compliant and readily manufacturable they are attractive for use where safety and customizability are a priority. While different types of SPAs can be found to match the force performance requirements of a variety of applications, outlying system-level issues of robustness, controllability, and repeatability are not traditionally addressed at the actuator level. The SPA pack architecture presented here aims to satisfy these standards of reliability as well as extend the basic performance capabilities of SPAs by borrowing advantages leveraged ubiquitously in biology; namely the structured parallel arrangement of lower power actuators to form the basis of a larger, more powerful actuator module. An SPA pack module consisting of a number of smaller SPAs will be studied using an analytical model and a physical prototype. For a module consisting of four unit actuators an output force over 112 N is measured, while the model indicates the effect of parallel actuator grouping over a geometrically equivalent single SPA scales as an increasing function of the number of individual actuators in the group. A 23% increase in force production over a volumetrically equivalent single SPA is predicted and validated, while further gains appear possible up to 50%, reasonably bounded by practical limitations from material properties and manufacturability. These findings affirm the advantage of utilizing a fascicle structure for high-performance soft robotic applications over existing monolithic SPA designs. An active wearable belt will be presented to demonstrate the capability of SPA pack modules to affect human trunk posture while standing, while further work may enable active modulation of trunk angle during walking to provide corrective assistance or gait modifying perturbations.

Introduction

The natural characteristics of SPAs are especially well-suited to human-robotic interface applications, where an active device is designed to directly affect the human body. A variety of soft actuated wearable hand exoskeleton and glove devices have been developed to leverage the adaptability, natural bending motion, and relative strength of SPAs for assistive and rehabilitation applications [1, 2, 3]. A large body of work also targets augmentation of lower extremity muscle and joint work to improve healthy normal functionality for walking or restore and assist deficiencies in gait dynamics [4, 5, 6, 7]. This latter group of applications which require high forces have primarily utilized a particular type of SPA, the Pneumatic Artificial Muscle (PAM) also known as the McKibben actuator. At present, these actuators have provided the only successful demonstration of SPAs in this high performance regime. This work seeks to develop and employ a new type of SPA architecture to service this realm while also permitting additional unique, advantages critical to reliable robotic systems.

Methods

Individual SPAs are fabricated from silicone rubber (Elastosil®M4601) and SPA packs of four unit actuators are assembled using a low-elastic modulus silicone rubber (Ecoflex®00-30) to join them. Using a single-axis load cell and a linear constraining test fixture, the force output of module inflated to 200 kPa was measured. To convert the linear action of a pack to bending motion, an inextensible sheet of fabric is attached to only one "face" of the flat actuator pack using SilPoxy® flexible adhesive.

A wearable belt is fabricated from 1.5" inextensible nylon webbing and 1" elastic straps, sewn together. From the same materials, an enclosure is also fabricated for each of four SPA packs produced, to provide a structural interface with the belt. A band of hook-and-loop fasteners is included along the belt and on each bending-type SPA pack enclosure to enable attachment and reconfigurable positioning of the modules. Finally, an outer, inextensible belt is used to constrain the actuator packs and ensure transmission of force and bending moments to the user.

To initially characterize the belt, a test platform was constructed with human proportions and used to measure the maximum vertical traction force and maximum moment applicable by four modules distributed evenly around the circumference of the "waist". The frequency response of blocked force to a range of sinusoidal pressure inputs was measured to obtain a system bandwidth, and the angular position of the "torso" segment of the test platform was measured using an accelerometer to demonstrate closed-loop PID position tracking of the test system. A final test of robustness was conducted by closing off individual SPA units in a given pack to simulate failure and the resulting trajectory under PID control was recorded.

The actuator belt was then tested on human subjects with four bending modules positioned in pairs on the medial-lateral plane at the hips and below the rib cage. Subjects were instructed to stand with arms crossed, feet together, and eyes closed while listening to white noise (rainfall) to disguise visual and audio effects of the pressure regulator and valves used to control the belt. A low frequency (0.1 Hz) sinusoidal control input was used to drive the belt in alternate directions and subjects were asked to "follow" the belt as if it were the guiding hands of a physical therapist or trainer. The angular position of subjects was recorded using an accelerometer attached by a tight elastic strap around the chest. Raw output data was low-pass filtered at 6 Hz.

Results

Individual SPA pack characterization revealed a linear force output capacity of 112 N per module, although measurement of the belt consisting of four modules shows 468 N total vertical force, which corresponds to a slightly higher average force capacity of 117 N per pack. The maximum moment measured using the test platform was shown to be 18 Nm.

The test of robustness indicated an asymmetric decline in capability under PID control, but the maintenance of overall tracking behavior.

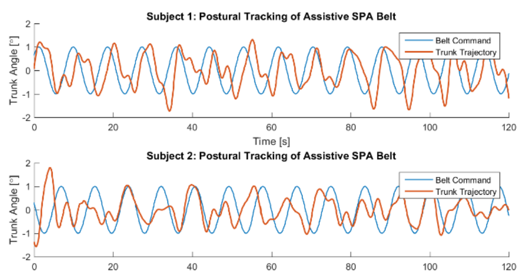

Figure 1 - Tracking of human subjects' trunk angle to sinusoidal SPA belt control signal

From human subject testing, the wearable SPA belt successfully demonstrated the ability to influence trunk posture in standing, as shown in Figure 1. Using FFT analysis, the dominant mode of both subjects' response trajectories were found to match the frequency of the input sinusoids at 0.1 Hz.

Discussion

The SPA packs shown here offer an alternative source of actuation for high-force wearable devices, or any application that may benefit from safety, reliability, and customizability. Drawing inspiration from biological analogs, parallel grouped SPAs afford advantages of robustness to failures, and modularly scalable force output not available from other soft actuator designs. The potential is illustrated by the short evaluation study presented of an example wearable SPA belt, but is not demonstrable of the actuators full capability. The active belt imposes a controllable influence on a human subject wearer, but from this study it is unclear how much this is directly mechanical and what amount may be informational feedback. Development of more adequate constraint and body interface features may yield stronger results from a wearable system or enable a study involving participants with partial or more severe postural impairments to benefit from a fully active soft wearable device for postural support.

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