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AN UNTETHERED ELECTRO-PNEUMATIC EXOSUIT FOR GAIT ASSISTANCE OF PEOPLE WITH FOOT DROP

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ABSTRACT

Individuals with foot drop caused by stroke or cerebral palsy (CP) have a particular need for robotic ankle exoskeleton. This paper proposes an untethered soft robot using an origami actuator to lift the toes of the wearer. The weight, connections, and complex control of the system are reduced through mechanical design. A compact and portable pneumatic system is designed to perform suction and compression with a single pump. The load test of the actuator shows the capability of 300N in 30 kPa. An untethered, simple and affordable robotic ankle exoskeleton is developed with the pneumatic actuator. The wearer can finish its simple 3-step donning procedure within 1 min.

Keywords: robotics, untethered, pneumatic actuator, ankle exoskeleton

NOMENCLATURE

3D	3-dimensional
kg	kilogram
kPa	kilo Pascal
lbs	pounds
mm	millimeters
N	Newtons
V	Volts

INTRODUCTION

Many individuals live with an impairment that causes an irregular walking gait, characterized as slow, asymmetric and inefficient [1] in which the individual would experience toe drag, high steppage gait, and foot slap. Stroke, Cerebral Palsy (CP), Traumatic Brain Injury (TBI) and Multiple Sclerosis (MS) are some of the leading causes of this foot drop impairment. Previous work [2-4] in this area has explored tethered and portable solutions utilizing mechanical-based exoskeletons, motor-driven systems, or large external components to drive the actuator. Traditionally, assistive exoskeletons have been built with rigid links [5]. Due to their limitations arising from joint misalignment [6], natural movement restriction, excessive cost and weight [7], they became an unappealing method of assistance.

The benefit of using the origami actuator is the simple and inexpensive manufacturing process for the actuator and the high force to mass ratio. The use of negative pressure offers a safer way of actuation compared with artificial muscles driven by highly pressurized fluids [8]. Increasing demand for autonomous and wearable soft robotics has been prevalent in recent years. Researchers have developed various soft-inflatable exosuits [9, 10]. Untethered soft robotics has many promising applications in the medical, industrial, and task-level autonomy fields.

Therefore, we aim to design an untethered ankle exoskeleton through the process of (1) proposing new design for the fluid system (a Boxer 3KQ series quad diaphragm pump and two 3V1-06 solenoid valves), (2) minimizing the utilization of push-to-connect connections and tubes by 3D printing a valve connection block, and (3) developing the pneumatic control electronics that can regulate vacuum and pressure for the system architecture components.

DESIGNING THE PNEUMATIC ACTUATION SYSTEM

The goals were to execute an optimized and simple system:

i. Reduce the weight of the system (make it portable)
ii. Design a pneumatic circuit that can reduce the complexity of the control algorithm;
iii. Test the load for the designed pneumatic actuator.

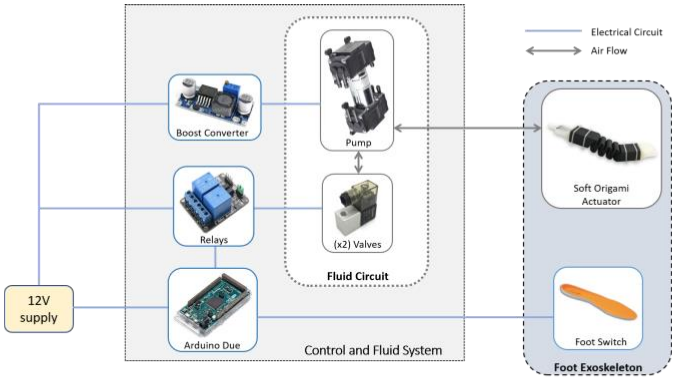

Figure 1: Architecture for the untethered system.

The system architecture as shown in fig. 1, illustrates the connections and relationship of the components in the system. Essentially, there are two circuits (1) electrical: supplying power to the components for operation and control, and (2) fluid: defining the path of airflow to the soft origami. Our soft origami was modeled similar to the operation and performance of Harvard's linear zigzag actuator design [4]. As it is composed of fabric, a 3D printed nylon skeleton, and air, the device serves as a cost effective and efficient artificial muscle that ensures a higher rate of the safety for the user.

We utilized a 24V miniature quad diaphragm pump to generate the airflow within the system, connecting the inlets and outlets in series-parallel (fig. 2) to produce a force large enough to contract the actuator with the intention of also lifting the additional weight. Since a majority of the components operate at maximum voltage of 12V, we step up the voltage using a boost converter. The force produced by the pump can be managed by reducing the voltage but maintaining it above the operational value.

The single assembly of two 3/2 solenoid valves is a significant contribution to the system's simplistic and compact design (fig. 3). We design a block to connect both valves, as well as imbedding the cross connection from the fluid circuit diagram. Several push-to-connect fittings were then added to complete the configuration. After assembly, this portion of the system weighs 0.34 kg (including the 6.35 mm tube connection), with the following dimensions: L: 100.6mm, W: 63.98mm, H: 59.26mm.

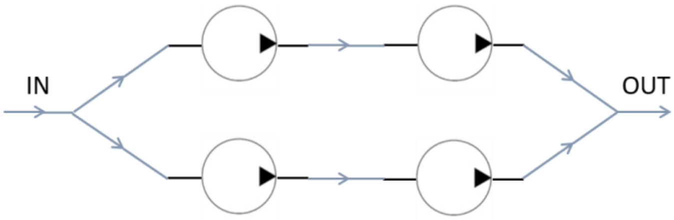

Figure 2: Pump series-parallel configuration.

This valve assembly has two ports that connect to the pump, two ports go to the atmosphere and one port is connected to the actuator. This assembly has 5 ports and 2 positions, one for suction and one for compression, hence making it similar to a 5/2 valve after assembly. The pump continuously flows air into the system, allowing the solenoid to direct the course of flow as it switches positions. Position 1 will cause depressurization in the actuator, and position 2 will produce pressure. In addition, our valve has two secondary positions that an ordinary 5/2 valve does not have, resulting in a total of four states (A–D) as shown in Fig. 5.

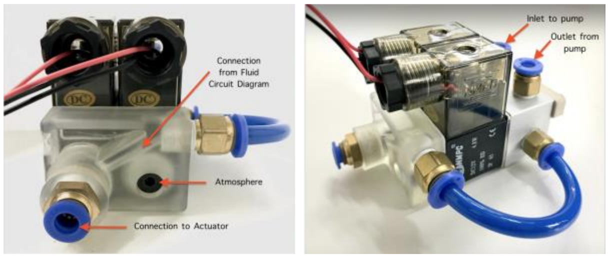

Figure 3: Single valve assembly. (Left) Front view. (Right) Side view.

(1) Expansion with continuous compression
(2) Contraction with continuous vacuum
(3) Static Contraction (maintaining a depressurized state of the actuator; air flowing through atmosphere)
(4) Static Expansion (maintaining a pressurized state of the actuator; air flowing through atmosphere ports)

These states are important in order to achieve a natural and fluid walking motion. Ordinary 5/2 valves have one solenoid which can only switch the valve between two positions – suction or compression. Our valve can switch between suction or compression if both solenoids are energized at the same time; or you can energize one solenoid to hold a constant pressure within the actuator if the person stops walking. Another limitation to ordinary 5/2 solenoid valves is that most are pilot operated and need a minimum required pressure to operate properly, whereas our system will operate despite the amount of pressure generated within the system.

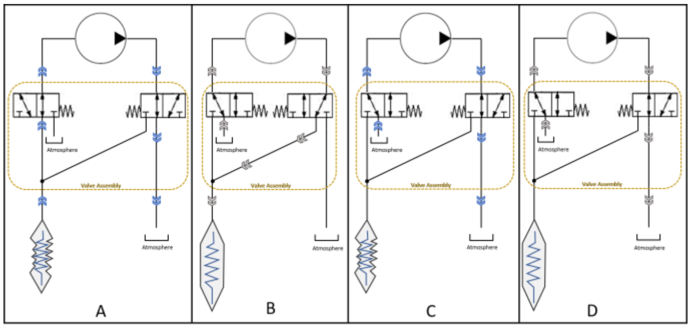

Figure 4: Fluid circuit of system architecture. (A) Position 1-actuated state- of solenoid valves for vacuum. (B) Position 2-normally closed state- for compression. (C) Position 3-Static Contraction. (D) Position 4-Static Expansion.

ELECTRIC CONTROL SYSTEM

The control system consists of an Arduino Due as the microcontroller, a foot switch and two relays – each connected to a separate solenoid valve. The foot switch sends signals to the microcontroller, indicating which position the solenoid should shift to. As previously mentioned, since there are two solenoids in the system, the ability to switch the positions of the solenoids independently can give us more options on how we can control the operation of the device. The algorithm for the control system will need to work for the following conditions phases of Gait: flat foot (standing), toe off and heel strike.

(1) Flat foot (standing): maintaining the static expansion form, this will be the equilibrium state as well as the state in which both heel strike and toe off are triggered
(2) Toe off: triggering the electrification of both valves to depressurize the actuator and lift the users' foot off the ground when taking a step
(3) Heel Strike: triggering the de-electrification of both valves, pressurizing the actuator to return the user's foot to equilibrium in order to plant it on the ground without injury

Designing this electric control system provides the use of less complex algorithms for the microcontroller.

Load tests were conducted after manufacturing and assembly. Different loads ranged from 0 to 300 N were tested and the pressures were measured.

DESIGNING THE ORIGAMI ACTUATOR

The goal in this phase was to design simple and affordable apparel to assist ankle dorsiflexion and plantarflexion. Fig. 5 shows the wearable part made of 3D printing and nylon fabric.The origami acturator is composed n strechchable origami as the skeleton and a Nylon fabric skin warpped aournd it. The two ends of the actuator are connected to the braces on wearer's shank and foot.

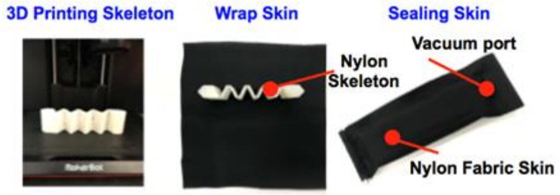

Figure 5: Total displacement of soft origami from the exerted force of the pump.

RESULTS

From its expansion to the contraction state, the soft origami has a displacement of approximately 7.62 centimeters, which is sufficient for the assistance of ankle movements (fig. 6).

From Fig. 7, the load can reach 300 N with 30 kPa, which is larger than pressure-driven method that produces no more than 60 N at 3 kPa [9]. This can be comparable to the lightweight actuator designed by Wiszomirska et al. [11].

Fig. 8 illustrates the key features of the ankle exoskeleton. The entire system is mounted as a single unit onto the wearer's body, with the heaviest components (battery pack, vacuum pump, and controller) affixed at the hip, to reduce inertia. Its novel actuator is a pneumatic artificial muscle, which is securely attached as a link between the shank and the foot.

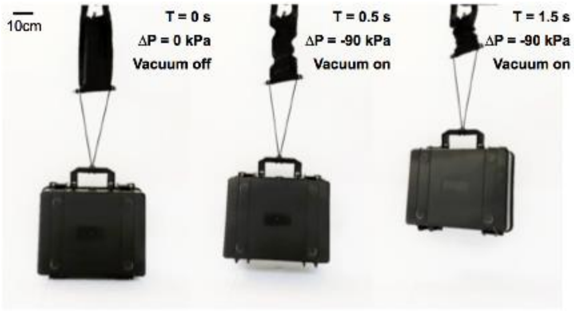

Figure 6: Lifting test (5.5 kg) of soft origami from the exerted force of pump.

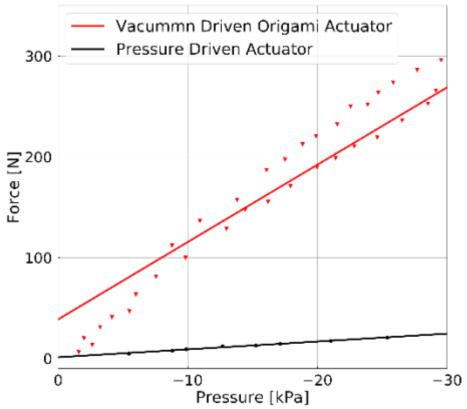

Figure 7: Load test with varied forces.

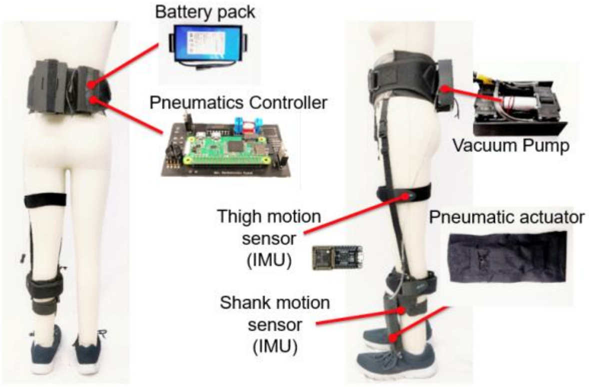

Figure 8: Overview of the modular pneumatically-driven ankle robotic system. The pneumatic control board consists of a pressure sensor, a microcontroller, a solenoid valve, and a transistor to regulate a vacuum pump.

A key ergonomic feature of our exoskeleton is its simple 3-step donning procedure, which takes less than 1 minute on average. As shown in Fig. 9, the wearer first straps the waist belt, around his/her waist. The second step is to wear the shoe and securely strap the calf-wrap around the calf. The final step is to fasten the clip-on straps on both sides of the leg, after which the wearer can start walking. The simplicity and affordability of our robotic apparel make it an ideal assistive technology.

Figure 9: A subject wearing the prototype of the vacuum-driven soft wearable robot for ankle assistance.

CONCLUSIONS

In this paper, we introduced an untethered ankle exoskeleton that can assist walking for the wearer. While simple and lightweight, our pneumatic actuator can reach 300 N in 30 kPa. The wearer can finish its simple 3-step donning procedure within 1 minute. In the future, the control algorithms will be developed to evaluate the asstist performance of the exoskeleton.

ACKNOWLEDGMENTS

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