Design and Validation of an Antagonistic Wearable Robotic Training Device for the Ankle

S. Mujica and J. Villalona, M. Coram, A. M. Okamura, *Fellow, IEEE*, C. du Pasquier

***Abstract*— Foot drop, characterized by dorsiflexion weakness, poses mobility challenges and increased fall risks, particularly among elderly individuals affected by nerve compression and stroke. With a growing elderly population projected to strain healthcare resources, there is a pressing need for affordable, non-invasive, at-home therapies to improve independence and quality of life. We introduce a soft rehabilitative robotic device integrating pneumatic fabric actuators for at-home dorsiflexion rehabilitation. Initial simulations show that increasing actuator volume dramatically increases its bending stiffness, especially for even cross-sections. Testing further shows that volume increase nearly doubles the maximum forces applied in dorsiflexion, up to 18 N at 70 kPa. These results motivate further development of a comprehensive testing platform to evaluate device efficacy and safety. Future research will focus on optimizing the sock's design and conducting user trials to assess muscle function using electromyography.**

I. Introduction

Foot drop, characterized by the inability to lift the forefoot due to dorsiflexion weakness, significantly limits mobility and increases fall risk [1], [2]. Foot drop results from conditions like nerve compression and stroke, which disproportionately affect the elderly, and can lead to reduced autonomy and quality of life. With 20% of the U.S. population expected to be over 65 by 2030 [3], there is a pressing need for affordable, non-invasive, at-home therapies to promote healthier, more independent living for the elderly.

Treatment for foot drop regularly involves an ankle-foot orthosis or functional electrical stimulation (FES), which are focused on improving gait, and thus require weight-bearing [4]. For partially immobilized patients following trauma, injury, or stroke, active engagement in repetitive, intense motion cycles has shown to improve neuroplasticity more effectively than passive exercise, where the patient is not cognitively engaged [4]. Foot drop patients are often treated with physical therapy (PT) to maximize function recovery. However, PT attendance can be challenging due to accessibility, transportation, and cost.

To address these challenges and reduce the financial burden on patients and healthcare systems, research has shifted towards robot-assisted therapy. Lower-limb robot-therapy has primarily focused on assisting and improving gait using exoskeletons [5], [6] or bulky leg-mounted pneumatic devices [7], [8], which requires ambulation. While some stationary solutions exist for patients in the acute phase of injury, they often rely on complex mechanical designs unsuitable for home use [6]. Both exoskeletons and stationary solutions are designed for clinical settings, failing to address accessibility and cost concerns.

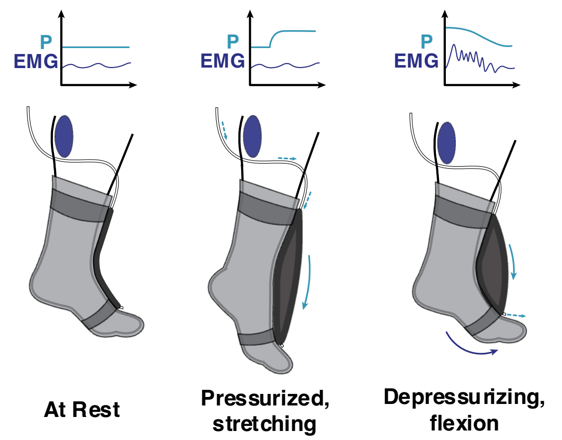

Figure 1. Ankle Device Overview: the fabric actuator integrated in a compression sock with force anchoring; it forces the foot down once pressurized; dorsiflexor activation is measured using EMG; the expected pressure and EMG readings for each state are shown above; teal arrows represent force applied by the actuator, dashed teal lines are air circulation, and purple arrow is applied force by the user.

This research aims to develop a cost-effective, comfortable, soft rehabilitative sock for at-home dorsiflexion rehabilitation. We designed, simulated, and tested pneumatic fabric actuators that can be integrated into a compression sock, providing both ankle stretch and resistive strength training (Figure 1). A test platform emulates the extended ankle angle to test our actuators.

II. Actuator Designs

In this study, we compare three fabric pneumatic actuator designs. They are manufactured using 70D thermoplastic polyurethane (TPU) coated ripstop nylon that can be bonded to itself by melting the TPU using ultrasonic welding. Its material properties are reported in [9]. Inextensible fabric ensures that the uninflated actuators are flat, which promotes comfort and wearability.

All three types of actuators measure 63.5 mm × 108 mm, sized to fit over the foot and ankle of 95% of the population [10]. The main variables are the number of channels in the main pouch, and the addition of origami like folds that increase the inflated volume. In the first actuator (‘No Folds’ in Figure 2), the pouch is simply divided into three channels that run

*This research is supported in part by National Science Foundation grant # 2301355.

S. Mujica, J. Villanova, M. Coram, A.M. Okamura, and C. du Pasquier are with the Department of Mechanical Engineering at Stanford University, CA 94035 USA (corresponding author phone: 650-736-3458; e-mail: cosimad@stanford.edu).

parallel to the length of the actuator. In the second ('Two Folds'), the two side channels have an added fold. In the third ('Four Folds'), the actuator is divided into five, and the two channels on either side of the center each have added folds. Our design hypothesis is that the folds provide additional volume, so the bending stiffness of the actuator increases, which translates into more dorsiflexion effort.

III. Preliminary Results

A. FEA

Finite element analysis (FEA) was performed using Abaqus CAE 2021, a blackbox solver. We use two *Dynamic/Explicit* steps to test our actuators, with a mesh size of 2.5 mm, and using the material parameters from [9]. The actuators are first inflated to 25 kPa using the boundary conditions for a 3-point bending test. Then, a *Point Load* of 0.05 N is applied on a node set halfway through the length of the actuators.

Table 1 shows the deflection and flexural modulus calculated based on the FEA results. As expected, increasing the volume of the actuator has a nonlinear stiffening effect. The stiffening effect is more marked when the inflated actuator cross-section is even across the channels.

Table 1 FEA 3-Point Bending Results

	No folds	**2x folds**	**4x folds**
Deflection	1.48 mm	1.09 mm	0.536 mm
Flexural modulus	140.7 kPa	179.4 kPa	387.6kPa

B. Testing

We performed preliminary force transmission tests of our actuators using a test setup in which actuators are angled at 120°, mimicking the position of an extended foot (Figure 2). Force is measured using a Nano 17 sensor (from ATI Industrial Automation).

Our results show that the first actuator, with no folds, applies an even force after ~20 kPa. This indicates that it cannot inflate much beyond that pressure, and thus plateaus. In contrast, the actuators with two and four folds increase their force quasi-linearly with pressure, since they can accommodate more volume. This linear increase will allow us to adjust the actuator force to a patient's muscular capacity.

Based on the FEA results, we expected that the four folds actuator would outperform the rest. However, the manufacturing complexity of adding the folds might have led to leaks in the actuator and thus weakened its force transmission. The design and fabrication need to be streamlined to ensure airtightness.

Our next steps include further characterizing the device and building a platform that more closely emulates the geometry and resistance in the ankle. Once proper function and patient safety are confirmed, we will proceed with user testing. Initially, we will focus on healthy subjects to measure how different pressures and relief-valve settings affect muscle function using EMG, as shown in Figure 1.

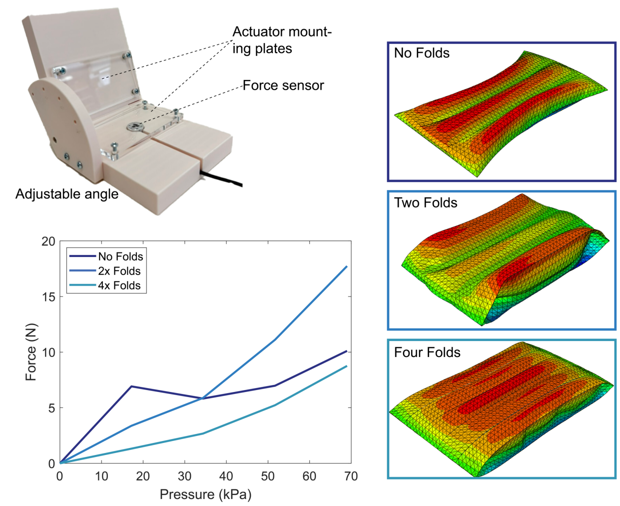

Figure 2. Preliminary force test results; top left: test setup; bottom left: force-pressure curves; right: inflated actuator FEA models

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