Soft Robotic AFO for Active Stroke Rehabilitation

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Index Terms—Soft Robotics, Wearable Robotics, Mechatronics, Rehabilitation

1 \textbf{PROJECT SUMMARY}

Our team presents a pneumatic soft robotic ankle-foot orthosis (SR-AFO) to improve gait abnormalities in impaired individuals treated using rehabilitation or ankle braces. Our novel design is lightweight and operates in multiple degrees of freedom to provide active assistance in ankle plantarflexion and inversion/eversion support while walking.

2 \textbf{IMPACT TO WEARABLE ROBOTICS INDUSTRY}

Ankle-foot orthoses (AFOs) are the most commonly-used orthoses available to patients, accounting for as many as 26\% of all orthoses provided to patients in the United States \cite{1}, \cite{2}. In particular, AFOs are commonly prescribed for stroke victims suffering from hemiparesis, which affects around 80\% of stroke survivors \cite{1}, \cite{3}, \cite{4}. According to the 2002 World Health Report, around 15 million people suffer from strokes each year, yielding potentially as many as 8 million survivors affected by hemiparesis \cite{5}, \cite{6}. While there are many versions of AFOs available on the market, they are largely made out of rigid materials like plastics and carbon fiber \cite{1}, \cite{2}. With the rise in popularity of the wearable robotic industry, new robotic devices are being created to replace existing rehabilitative technology. The field of soft robotics is rapidly becoming a trend for wearable and rehabilitative robotics due to the compliant, affordable, and comfortable nature of the materials used.

The team working in Arizona State University’s Neuromuscular Control and Human Robotics Laboratory presents one such wearable robotic device to improve rehabilitation for gait-impaired individuals using a soft robotic ankle-foot orthosis (SR-AFO). Traditional AFOs are designed to provide ankle support to the impaired individuals without active corrective action. This can subsequently lead to complications with mobility, increased risk of injuries, or pain due to gait adaptations attributable to limited ankle function \cite{7}, \cite{8}. The SR-AFO integrates soft, pneumatic actuators made from garment-like fabrics that simulate the behavior of the soleus (SOL) and gastrocnemius (GA) muscles in the walking gait cycle into the traditional rehabilitative AFO design, reducing the amount of muscle activation needed by the patient \cite{9}. This novel design operates in multiple degrees of freedom (DoF), providing both assistance in ankle plantarflexion and inversion and eversion support, two critical motions which occur at different points in the gait cycle \cite{9}, \cite{10}. The SR-AFO is designed to provide...
Fig. 2. Logic control box for the SR-AFO exosuit, which controls the timing of actuation, monitors pressure levels, and collects kinematic behavioral data of the user through FSR sensors.

Fig. 3. (a) Side and posterior views of the SR-AFO attached over the wearer’s shoe and secured at the knee, actuator pressure at atmosphere (inactive). (b) Side and posterior views of the exosuit, actuator pressure at 100 kPa (active).

safe, active assistance at the precise intervals where it is needed while walking without impacting the comfort or range of motion (ROM) of the wearer. Inversion/eversion (IE) actuation is required in the loading response right after heel strike in order to improve ankle stability in the mediolateral direction. In fact, IE actuation may even provide a slight assistance to prevent “foot slap” in this gait phase. Plantarflexion actuation is required to assist push off in the late stance phase [11].

The main goal of the project is to produce a wearable robotic AFO that achieves a higher level of performance than competing designs. A “higher performing” device would accomplish three main goals: (1) increase human comfort and adaptability to the orthosis, (2) extend the rehabilitative capabilities of current AFO designs, and (3) have a competitive market price. The team believes that the proposed SR-AFO project attains each of these goals, and therefore predicts that this project will greatly impact traditional methods of gait rehabilitation.

TABLE 1
Go/No Go Decision Points and Constraints

<table>
<thead>
<tr>
<th>Design Requirements</th>
<th>Characteristics</th>
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</thead>
<tbody>
<tr>
<td><strong>Design Considerations and Criteria</strong> [12] [13]</td>
<td></td>
</tr>
<tr>
<td>Soft, compliant material</td>
<td>Neoprene, Spandex and Nylon</td>
</tr>
<tr>
<td>Low profile</td>
<td>~5mm</td>
</tr>
<tr>
<td>Easy don/doff</td>
<td>≤30s</td>
</tr>
<tr>
<td>Light weight</td>
<td>≤200g</td>
</tr>
<tr>
<td><strong>Motion and Force Considerations</strong> [14], [15], [16], [17], [18]</td>
<td></td>
</tr>
<tr>
<td>Support Plantarflexion</td>
<td>1.6 Nm/kg</td>
</tr>
<tr>
<td>PF Muscle Assistance</td>
<td>GA, SOL muscles</td>
</tr>
<tr>
<td>Assists Pre-Swing</td>
<td>Active during late stance</td>
</tr>
<tr>
<td>Minimum ROM</td>
<td>≥30° Dorsiflexion-Plantarflexion (DP)</td>
</tr>
<tr>
<td>Lateral Stiffness</td>
<td>70 Nm/rad</td>
</tr>
<tr>
<td><strong>Controls Criteria</strong> [11], [19], [20]</td>
<td></td>
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<tr>
<td>Perturbation Timing</td>
<td>+10% natural weight on toe</td>
</tr>
<tr>
<td>Gait Cycle % Assisted</td>
<td>40% to 60% of gait</td>
</tr>
<tr>
<td>Pressure Threshold</td>
<td>100 kPa</td>
</tr>
<tr>
<td>Walk at a natural pace</td>
<td>≥0.8 m/s</td>
</tr>
</tbody>
</table>

3 Novelty of Design

Our soft robotic AFO is a novel advancement that extends rehabilitative capabilities beyond the basic assistance provided by rigid AFO designs. The SR-AFO is a lightweight, compliant alternative to traditional AFOs or heavy and expensive exoskeletons, and can be worn as clothing during use. The SR-AFO is affordable and provides active assistance in multiple DoF without adding excessive weight to the user’s leg or restricting natural motion [9], [10].

4 Design Plan

To achieve the final production of a higher-performing soft robotic AFO, a five-year design timeline for product optimization is proposed (Fig. 4). Key Go/No Go decision points occur at each level of the design plan to reflect critical design requirements (Table 1). Human subject experimentation is integrated into the design process [21]. The team will partner with Dr. Carolyn Kinney and Dr. Megan Eikenberry1, clinicians at Mayo Clinic and Midwestern University, to ensure that the SR-AFO functions optimally for gait-impaired patients. Clinical trials are scheduled for September 2020. Pending the success of the clinical trials, the final design will be moved to production, and permanently implemented into rehabilitation facilities.

5 Intellectual Property and Funding

The team will develop a method to make the system portable as in previous work [22]. Portability allows customers to purchase the orthosis for at-home rehabilitation. Designing for personal comfort will naturally draw consumers to our product. The corrective ability of the SR-AFO across many gait abnormalities cements its market demand. A patent has been filed for an early version of the prototype [23], and the team plans to file a second patent for the new design prior to commercialization.

1. Dr. C. Kinney, MD, Department of Physical Medicine and Rehabilitation, Mayo Clinic, AZ, and Dr. M. Eikenberry, DPT, Department of Physical Therapy, Midwestern University, AZ
Fig. 4. A detailed plan presenting current work done on the SR-AFO project, as well as the continued plan project out until May of 2021, where future funding and partnerships will be critical in the success and validation of the SR-AFO.

6 **ANTICIPATED USE OF $5,000**

The current SR-AFO prototype costs approximately $100.00 to manufacture, as shown in Table 2, excluding the cost of the controller, electricity and compressor used to actuate the exosuit. The cost of the control and pneumatic system is outlined in Table 3. The manufacturing cost of the current prototype is comparable to the price of plastic AFOs that do not include any robotic components. Additionally, the team’s SR-AFO project eclipses the cost of rigid robotic competitors, which can cost up to $80,000 to implement for similar rehabilitative studies [24].

The $5,000 research budget will allow the team to improve the final design, particularly by addressing the use of a tether between the control box and the AFO. A tether has been used to contain wiring necessary to read force data from toe and heel sensors within the shoe. The air supply used to actuate the pneumatic system is also tied to the tether. The team proposes several alternatives to the existing tether, such as the integration of wireless inertial measurement unit (WIMU) sensors connected to a smaller control box that could be fixed to the patient. This alternative would allow the SR-AFO and its controller to be more portable, as it would only require a connection to housed air supplies. The team also intends to investigate the integration of an improved portable pneumatic system as used in early versions of the SR-AFO [22].

Additionally, the team is currently working on a design iteration that would integrate plantarflexion assistance and inversion/eversion support into the human gait cycle. Currently, the SR-AFO has the capacity to perform both functions, particularly in the actuator design and timing of pneumatic actuation. The team’s next step is to integrate both functions together seamlessly, so that both inversion/eversion support and plantarflexion assistance occur at precisely the optimal moment for assistance within the gait cycle for individuals with abnormal or highly varied gait patterns.

The team has not yet implemented such design changes due to research budgeting, and therefore a $5,000 increase would allow these design improvements to be realized. Such improvements ensure that the team’s SR-AFO incorporates and refines many thoughtful design features that would prompt a customer to select our product over a competitor’s.

**ACKNOWLEDGMENTS**

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**REFERENCES**


