Proceedings of the 2019 Design of Medical Devices Conference
DMD2019
April 15, 16-18, 2019, Minneapolis, MN, USA

DMD2019-3231

DESIGN OF THE PLAYSKIN AIR™: A USER-CONTROLLED, SOFT PNEUMATIC EXOSKELETON

Bai Li, MS[1], Ben Greenspan, BS[1], Thomas Mascitelli[2], Michael Raccuglia[3], Kayleigh Denner[3], Raymond Duda[3], Michele A. Lobo, PT, PhD[1,4]
University of Delaware
Newark, DE, USA

ABSTRACT

Many children have an upper extremity disability leaving them unable to explore the environment around them. Hard exoskeletons can provide support to lift a child's arms up against gravity, but these devices are generally large and obtrusive leading to low adherence. Children often prefer to have limited arm function rather than wearing such a device. Our lab has previously designed a passive soft exoskeleton to lift children's arms, but this did not allow for user control and was limited in the length and weight of arm it could support. Building off of this research, we have created the preliminary design for a user-controlled pneumatic soft exoskeleton that may allow users to independently raise and lower their arms.

Keywords: Assistive medical device, soft exoskeleton, exoskeleton, functional fashion, rehabilitation technology

INTRODUCTION

For children who have an upper extremity disability, moving their arms against gravity can be a very difficult task. This can make it challenging to explore the environment, which can negatively impact developmental outcomes [1]. It can also make it challenging for children to perform activities of daily living such as academic and self-care activities [1]. Therefore, it is critical to develop rehabilitative technologies, such as exoskeletons, that can assist upper extremity mobility and function. An exoskeleton is a medical device "worn external to the body that mimics the human exoskeleton by assisting and supporting movement" [2].

The vast majority of current active exoskeletons are rigid, heavy, and bulky, which can lead to low adherence. These exoskeletons have plastic and metal components and are powered by electric motors [3]. Compared to these hard exoskeletons, pneumatic actuators with a low-profile structure and soft material provide a potential novel solution for this challenging problem.

Currently there are three main types of soft pneumatic actuators. The first acts linearly, most commonly in the form of a McKibben air muscle [4]. These consist of a flexible tube surrounded by a braided sleeve that increases in diameter and shortens in length when pressure is added [4]. Next, there are flexible tubes that start in a bent orientation, stiffening and straightening when inflated [5]. Lastly, there are inflatable bladder systems that behave similarly but are designed to generate forces over larger areas [6].

Previously, our lab developed the Playskin Lift™, a passive exoskeletal garment to improve arm function for infants and toddlers with arm movement impairments [2]. The Playskin Lift™ uses bundles of steel wire inserted into vinyl tunnels located under the arms that act as springs [2]. This lifting effect reduces the force of gravity on the arms, allowing children to move more easily. This device has been shown to be effective in supporting children's arms to improve their reaching and play abilities. Significant improvements in hand function are observed within sessions when infants and toddlers with arm weakness wear this device; improvements in independent function are also observed for these infants and toddlers when the device is used for daily intervention across time [7][8]. These distal improvements are facilitated by the proximal support provided at the shoulder. However, the Playskin Lift™ is ineffective for children older than three years old who have longer, heavier arms [7]. The device is also limited for older

[1] Physical Therapy Department & Biomechanics & Movement Science Program
[2] Mechanical Engineering Department
[3] Biomedical Engineering Program
[4] Corresponding author: 540 S. College Ave, Newark, DE 19713; malobo@udel.edu.

users as it requires an external caregiver to insert or remove the wire bundles and the level of support cannot be adjusted in real time by users to meet their changing needs across tasks [6].

Building off of this research, we realized there was a critical need for an exoskeleton that could extend to an older population with longer, heavier arms, and for the solution to be user controlled. Based on reported user needs and wants, it was decided that a pneumatic device would work best for this because of its potential to yield a relatively low profile, comfortable concept that could be integrated comfortably into users' clothing.

METHODS

2.1 Bladder Construction

After experimenting with air muscles and tubes that straighten when inflated, it was decided that a bladder would be a successful solution for this problem. The bladder allows for forces to be distributed more evenly and provides a more stable base for the arm to rest on. Some design challenges included provision of support for the weak elbow, wrinkling under the axilla when bent, and designing the bladder shape to move the arm in the desired direction when inflated. Our research team came up with four different air bladder shapes: 1) Rectangle, 2) Y, 3) box pleat, and 4) bag (patterns shown in Figure 1).

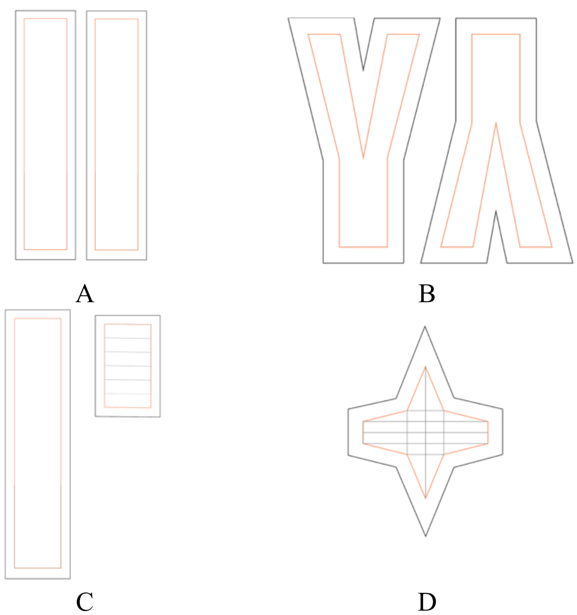

FIGURE 1: Patterns for the four bladder shapes tested: A) Rectangle, B) Y, C) Box Pleat, and D) Bag

First, bladder patterns were drawn using EFI Optitex CAD (EFI^{TM}) software. Next the shapes were cut out of muslin, stitched together where we intended to heat seal the edges, and stuffed with cotton to simulate what the shape would be like once inflated. We determined sizing to fit the arm of an 11-year-old test participant, including two lengths of the rectangle bladder (Table 1). Then bladders were produced with air-tight fabric (58" 200 D heat-sealable Oxford), heat-sealing (Impulse Sealer and DeWALT DWHTGR50) them together so that they produced the desired shape when inflated. The finished bladders are shown in Figure 2.

TABLE 1: Bladder sizes (in inches, without seam allowances)

Shape	Rectangle	Rectangle 2	Y	Box Pleat	Paper Bag
Height	9.5	16.5	15	10	4
Width	5	7	7	5	4

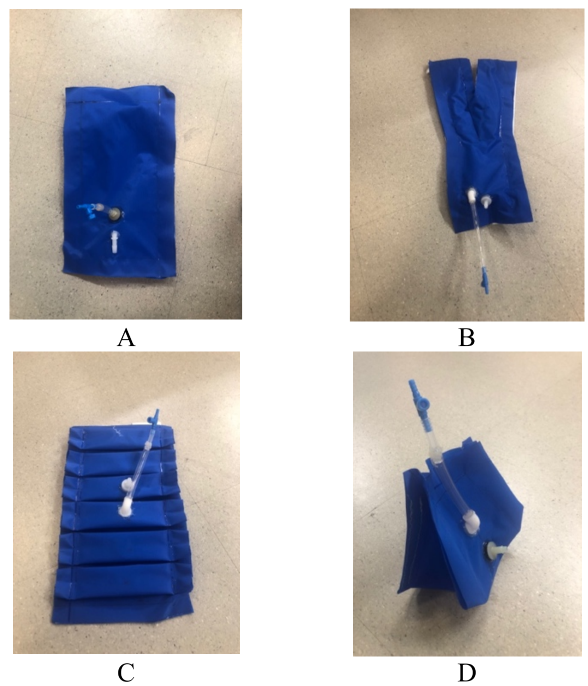

FIGURE 2: Four finished bladder shapes tested: A) Rectangle, B) Y, C) Box Pleat, and D) Paper Bag

After constructing the bladders, a custom testing apparatus (Figure 3) was designed to model the size (25.36 inches long) and weight (5.95 pounds) of an 11 year-old's arm [9]. The apparatus had a single degree of freedom joint at the shoulder, allowing for abduction. Each of the 4 shapes was inserted into a cover fabric over a slim-fit, long sleeve, soft shirt that was placed over the testing apparatus. Each bladder was inflated using a bike pump (Vibrelli & model: Performance Floor Pump) to the maximum angle the bladder would lift the arm. Pressure readings were recorded from the pike pump. Angle measurement was taken using the trakSTAR (Ascension, USA) motion analysis system with one IMU sensor mounted to the superior side of the arm. These results can be seen in Table 2.

Figure 3: Custom Testing Apparatus

TABLE 2: Maximum arm abduction angle and pressure (angle is reported in degrees; pressure is recorded as PSI)

Shape	Rectangle	Rectangle 2	Y	Box Pleat	Paper Bag
Angle	42.404	123.80	28.693	38.882	40.048
Pressure	10	20	0	0	0

It was found that the Y, box pleat, and paper bag shapes had consistent leaking issues (see pressure values in Table 2). To identify the source of the leaks, the bladders were submerged in water while inflated to see the air bubbles leaking from the bladder. It was identified that when heat sealing took place on a crease with more than two layers of fabric, the bond wasn't air tight between layers. This leaking could be mitigated with a more robust heat sealing technique, but for the moment, the rectangle shape bladder was selected to move forward.

For the final prototype, the rectangle 2 bladder was selected, (16.5 inches tall by 7 inches wide) because of its advantageous maximum arm abduction angle. This prototype was tested on an 11 year old child, and was able to lift the user's arm slightly over 90 degrees.

2.2 Inflation and Deflation Mechanisms

During initial testing, air traveled from the bike pump to a high-use backflow prevention one-way valve (McMASTER-CARR & model: High-Use Backflow-Prevention Valve). A second valve, which was 3D printed and sealed to the bladder using Gorilla Super Glue 15 Gram, connected to a 2-way air pump control valve that acted as the release valve. Silicone tubing (White Silicone Tubing & model: SCT-04-10) was used to connect the bike pump to the one-way valve and the 3D printed valve to the release valve.

Three different concepts were considered for inflation: 1) self-inflation from exhalation, 2) electric air pump, & 3) compressed CO_2 cartridges. Quickly after testing the self-inflation technique, it was discovered that this method was challenging, slow, and restricted users from engaging in conversation. Electric air pumps had two distinct flaws with their overall weight and noise when in operation. Compressed CO_2 cartridges proved to be a good choice because of their robust, well-tested design, and their common availability in multiple sizes. In the final prototype the compressed CO_2 cartridge (CyclingDeal & model: Threaded 16g) was connected to a pressure regulator (MRbrew & model: Mini CO_2 regulator with 3/8 thread) and then two solenoid valves (Plum Garden & model: ¼ DV 12V 2 way normally closed electric solenoid air valve) were incorporated to control the release of the gas.

The compressed CO_2 cartridge solution offers accessibility and affordability as it is commonly available in the market. The 16g size is relatively small and light, which reduces the weight of the device for the child and its bulkiness. Using the regulator allows for control over the rate of release of the CO_2 into the air bladder, effectively controlling the inflation rate of the bladder. This also offers a safety measure to ensuring the rate of release would not cause potential safety issues. We observed similar inflation time among pressures greater than 10 psi. Failure of the bladder seam occurred at 20 psi.

2.3 Clothing integration and user control

A slim-fit, long sleeve, soft shirt with a zipper in front was created to incorporate the bladders and minimize drift. A cover fabric was added to the garment which could house the air bladder as can be seen in Figure 5. This cover fabric maintained alignment of the bladder and spread the lifting force more evenly across the limb to better support the arm. The garment was made with a knit fabric and was customized for the 11-year-old boy in this pilot study. To make the garment pattern more accurate, we reproduced a customized virtual avatar with the dress form model provided by the EFI Optitex mannequin library [10]. A 2-inch-wide Velcro strap was attached under each sleeve of the garment, allowing for attachment and testing of multiple sized and shaped bladders. The current design of the Playskin Air™ operated through strapping the air bladder around the user at three locations: the midpoint around the armpit, and the two ends, as can be seen in Figure 4.

Figure 4: Clothing integration and user control Testing.

Multiple inputs including a phone app, capacitive touch, and myoelectric control were considered as the activation for the inflation mechanism, but ultimately one button for inflation and one button for deflation (Delinx & model: Button switches from 'DC 6V Air Pump Motor DIY Project Kit') proved to be the most intuitive for this early design for children. The research team found that the index finger would be a relatively beneficial location for both inflation and deflation buttons. A finger-belt mechanism could be worn without decreasing the functionality of the user's hand during daily activities.

The user depresses the inflate button to open a solenoid valve (Plum Garden & model: ½ DC 12V 2 way normally closed electric solenoid air valve) allowing air to travel from the CO_2 cartridge through a pressure regular and to the bladder, and depresses a separate button to open a solenoid releasing the air from the bladder to the environment. This system can be seen in Figure 5.

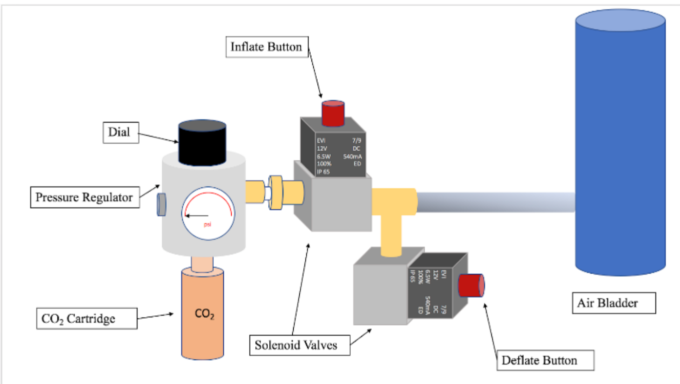

Figure 5: The final inflation/deflation concept design, which involves the solenoid valve, CO_2 cartridge, and pressure regulator.

RESULTS AND DISCUSSION

Preliminary results have shown that the Playskin Air™ can successfully lift the model of an 11-year old child's arm greater than 120 degrees. When integrated within a garment, it lifted a human 11-year-old child's arm greater than 90 degrees while being user controlled. This prototype incorporated the bladder shape, sealing technique, inflation mechanism, and user control method described. The final prototype can be seen in Figure 4.

Our team plans to continue moving forward making a more integrated and refined prototype. Next steps will include stitching the bladder into the clothing rather than using Velcro, eliminating the additional straps going around the torso, decreasing the size and weight of the control mechanism and integrating it into the clothing, more intuitively anchoring the inflation and deflation buttons, and mechanical testing to determine the optimal bladder parameters to lift arms of 4-14-year-olds. It is likely this integration and refinement process will better allow the bladder to contact the arm, and we expect this will result in a prototype that provides improved lifting support through a greater range of motion. Input from end users with arm movement impairments will continue to be incorporated throughout the refinement and integration process. The emerging prototype will then be tested on children with arm movement impairments to assess their perceptions and feedback on the device and whether the device supports them in a manner that allows for improved mobility and function.

ACKNOWLEDGEMENTS

We would like to thank the parents and children who have shared information regarding their wants and needs for this type of device, those participating in testing of prototypes, and research assistants helping with this project. This project is funded by the National Science Foundation (1722738).

REFERENCES

[1] Lobo, Michele A., Regina T. Harbourne, Stacey C. Dusing, and Sarah Westcott McCoy. "Grounding early intervention: physical therapy cannot just be about motor skills anymore." *Physical therapy* 93, no. 1 (2013): 94-103.

[2] Lobo, Michele A., John Koshy, Martha L. Hall, Ozan Erol, Huantian Cao, Jenner M. Buckley, James C. Galloway, and Jill Higginson. "Playskin Lift: Development and Initial Testing of an Exoskeletal Garment to Assist Upper Extremity Mobility and Function." Physical therapy 96, no. 3 (2016): 390-399.

[3] Young, Aaron J., and Daniel P. Ferris. 2017. "State of the Art and Future Directions for Lower Limb Robotic Exoskeletons". IEEE Transactions on Neural Systems and Rehabilitation Engineering. 25 (2): 171-182.

[4] Tondu, Bertrand, and Pierre Lopez. "The McKibben muscle and its use in actuating robot-arms showing similarities with human arm behaviour." Industrial Robot: An International Journal 24, no. 6 (1997): 432-439.

[5] Goldfield, Eugene C., Yong-Lae Park, Bor-Rong Chen, Wen-Hao Hsu, Diana Young, Michael Wehner, Damian G. Kelty-Stephen et al. "Bio-inspired design of soft robotic assistive devices: The interface of physics, biology, and behavior." Ecological Psychology 24, no. 4 (2012): 300-327.

[6] Segers, Patrick, Jean-Paul Belgrado, Andre Leduc, Olivier Leduc, and Pascal Verdonck. "Excessive pressure in multichambered cuffs used for sequential compression therapy." Physical therapy 82, no. 10 (2002): 1000-1008.

[7] Babik, Iryna, Cunha Andrea B., Moeyaert Mariola, Hall Martha L., and Lobo Michele. A. " Feasibility and effectiveness of intervention with the Playskin LiftTM exoskeletal garment for infants at risk." Physical therapy (In Press).

[8] Babik, Iryna, Cunha, Andrea B., and Lobo Michele. A. "Object play in children with arthrogryposis: Assistive and rehabilitative effects of the Playskin Lift™ exoskeletal garment." American Journal of Medical Genetics Part C special issue on Arthrogryposis Syndromes (Under Review).

[9] American Society for Testing and Materials. (1999). Standard tables of body measurements for boys, sizes 8 to 14 slim and 8 to 20 regular. West Conshohocken, Penns: American Society for Testing and Materials.

[10] "EFI Optitex", accessed October 30, 2018. https://optitex.com/