Design of a Hybrid SMA-Pneumatic based Wearable Upper Limb Exoskeleton

Alireza Golgouneh†[1], Eric Beaudette[2], Heidi Woelfle[3], Bai Li[4], Niharikha Subash[5], Amanda Redhouse[6], Mark Jones[7], Tom Martin[8], Michele A. Lobo[9], Brad Holschuh[10], Lucy Dunne[11]

{[1]golgo002, [2]beaud128, [3]woel0055, [5]subas015, [10]bth, [11]ldunne}@umn.edu, {[4]baili, [9]malobo}@udel.edu, {[6]aredhouse, [7]mtj, [8]tlmartin}@vt.edu

[1,2,3,5,10,11]Wearable Technology Lab, University of Minnesota, Minnesota, Saint Paul, MN, USA
[4,9]Department of Physical Therapy & Biomechanics & Movement Science Program, University of Delaware, Newark, DE, USA
[6,7,8]Department of Electrical and Computer Engineering, Virginia Tech University, Blacksburg, VA, USA

ABSTRACT

Upper limb mobility impairments affect individuals at all life stages. Exoskeletons can assist in rehabilitation as well as performing Activities of Daily Living (ADL). Most commercial assistive devices still rely on rigid robotics with constrained biomechanical degrees of freedom that may even increase user exertion. Therefore, this paper discusses the iterative design and development of a novel hybrid pneumatic actuation and Shape Memory Alloy (SMA) based wearable soft exoskeleton to assist in shoulder abduction and horizontal flexion/extension movements, with integrated soft strain sensing to track shoulder joint motion. The garment development was done in two stages which involved creating (1) SMA actuators integrated with soft sensing, and (2) integrating pneumatic actuation. The final soft exoskeleton design was developed based on the insights gained from two prior prototypes in terms of wearability, usability, comfort, and functional specifications (i.e., placement and number) of the sensors and actuators. The final exoskeleton is a modular, multilayer garment which uses a hybrid and customizable actuation strategy (SMA and inflatable pneumatic bladder).

CCS COCEPTS

• Human Computer Interaction (HCI), Interaction Devices

KEYWORDS

Soft Exoskeleton; Soft robotics; Wearable Technology

1 Introduction

Interventions allowing for upper limb mobility are especially important for children that may need assistance for performing activities of daily living (ADLs) [16]. It is estimated that nearly 5.6 million children under 18 years old have physical impairments that affect ADLs [9]. While the state of the art in assistive devices emphasizes rigid robotics and may even increase user exertion [2], there is a persistent need for assistive systems with more soft, flexible, lightweight, and unobtrusive form factors. The emerging discipline of soft robotics, which uses mechanically responsive soft materials to replace traditional hardware, offers promise for better wearability.

Soft actuators including pneumatic bladders and SMAs have widely been used in previous soft exoskeleton designs individually, owing to their ability in generating sizable linear forces/displacements [1,3,4,13]. Each of these actuation mechanisms have advantages and limitations. One way to overcome these limitations is to use them in a hybrid scheme. However, such hybrid actuation schemes require detailed design and engineering consideration to ensure the robotic systems complement one another appropriately.

In this paper, we present our mobility-assistive wearable prototype that combines different types of textile-friendly soft sensors and actuators. To generate assistive forces for upper limb motions, we designed a system which combines both pneumatic and SMA actuation to achieve shoulder abduction/adduction and horizontal flexion/extension. To accurately measure the resulting movements, textile strain sensors were used. The final soft exoskeleton design was developed through a 2-step iterative prototyping process: (1) integration of the SMA actuators and soft sensors, and (2) integration of the pneumatic actuators, SMA actuators, and sensing garment.

2 System Components

2.1 Soft Sensing

Bottom-thread coverstitched strain sensors have been shown to be capable of capturing joint motion in previous studies [5], and were used in both generations of the garment to capture shoulder motions. This sensor is made of Shieldex 235/34oz silver-coated nylon thread, directly sewn onto the base garment as the bottom thread in a coverstitch. The resistance of the sensor decreases as strain increases, due to the change in connectivity of the conductive threads that are sewn in a looped configuration [5]. Previous studies have shown that the response of the sensor changes linearly with respect to the strain amount (correlation coefficient r2>95%) [8].

2.2 Hybrid Soft Actuation

Broadly, wearable soft robotic systems have to overcome several physical/mechanical challenges to effectively support or manipulate a targeted body part: (1) the system should produce and transmit adequate force/torque to move a targeted body segment or limb, (2) it should be well-anchored to the body for leverage that is required during actuation, and (3) it should be able to apply a force vector without inhibiting mobility. The designed system also should also be in a form factor that is comfortable, unobtrusive, and suited for long-term use. With those requirements in mind, we focus our efforts toward two core technologies that present promise in this application: (1) SMAs to create linear forces/displacements to articulate the arm in the horizontal plane (i.e.,assist shoulder horizontal flexion/extension), and (2) pneumatic bladders that inflate to cause a change in shape and/or volume, to lift the arm (i.e., assist shoulder abduction). Therefore, the hybrid system approach offloads the weight of the arm to the pneumatic bladder system while leveraging the benefits of SMAs to drive horizontal limb movement.

2.2.1 SMA Actuators

SMAs are a type of material capable of transforming into a pre-trained shape when heated, the most commonly used being nickel-titanium (NiTi). In wire form, SMAs can only generate a displacement of 6-8%; in comparison, when in coiled form, SMAs afford large (>100%) active displacements maintaining significant forces [6,7]. In this system, SMA wires (Flexinol® wire, Dynalloy Inc., diameter 0.304 mm, nominal activating temperature 70°C) are formed into springs of 1.219 mm outer diameter, and heat treated at 450°C for 10 minutes to set their shape. SMAs have an inherent limitation since they only have a one-way shape memory effect, whereby they can only contract when actuated and must be manually reset. To circumvent this, the SMAs are housed in fabric braids which function as an antagonistic elastic force for the SMA actuation and allow for faster relaxation of the SMA when it is not powered. The SMAs were actuated through resistive/joule heating using an external power supply.

2.2.2 Pneumatic Bladder

Pneumatic bladders offer the benefit of providing variable levels of support to a body segment when inflated, and can be soft, lightweight, comfortable, and affordable for users [11,12,15]. Previous studies have shown that a wing-shaped pneumatic bladder made with heat-sealable fabric can provide the full assistance required to lift the arm of an 11-year old male [10,11]. In this study, the bladder design in Figure 1 provided vertical shoulder abduction/adduction.

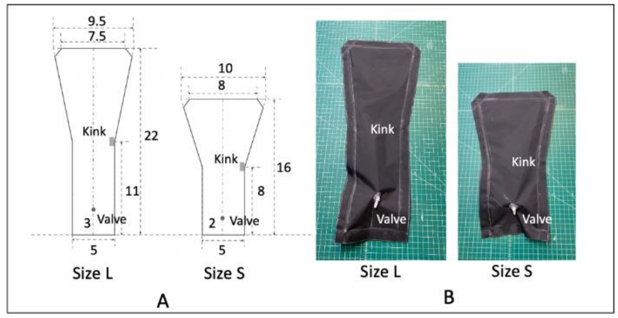

Figure 1. The sketch (left) and the photograph (right) of the fabricated inflatable pneumatic bladder, showing the dimensions (cm) of the bladder and locations of the inflation valve and kink

These bladders were made with Heat Sealable 70 Denier Nylon Taffeta (6606-108, Rockywoods Fabric) and fabricated using a SeamMaster High Profile Ultrasonic Sewing Machine (Sonobond Inc.) with a R1044 pattern wheel for combining Taffeta fabrics together. Figure 1 shows the valve that allows for bladder inflation and the kink design (1.27x2.54 cm) that was provided to decrease resistance for horizontal flexion/extension. A soft, perforated tube (5234K44, McMASTER) was incorporated into the bladder to address bladder crimping during actuation.

3 Garment Generations

3.1 Generation 1: Sensing and SMA-Actuation Garment

The first generation of the exoskeleton garment was designed to evaluate the capability of the soft strain sensors placed around the shoulder joint for capturing the wearer's joint rotations. In total, 18 sensors were sewn on the garment, 9 on each side (left and right), as shown in Figure 3. In order to localize the extension induced by body movements to the sensing area, the garment was designed in 3 parts, consisting of a non-stretchable fabric (100% cotton plain weave, center back/front and sleeves) separated by stretchable knit fabric in the sensing region (around the shoulder, 82% nylon, 18% spandex). The garment was made to fit tightly to maximize translation of body movements to the garment. Sensors lengths varied between 11.4 cm-15.2 cm. Sensors were evaluated through a series of movements, including single rotational, multi-rotational, and random, and compared to motion data

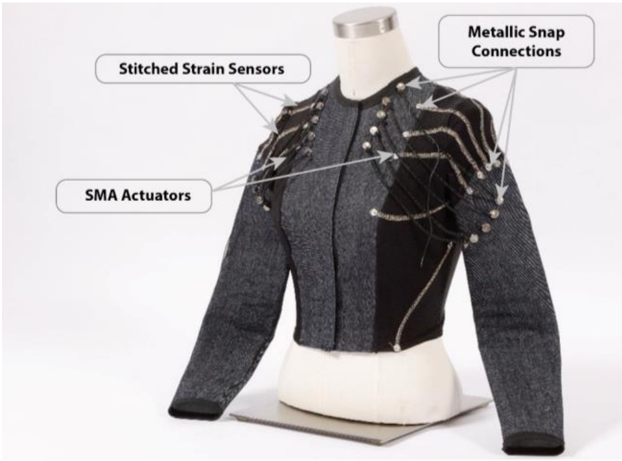

Figure 3. Generation 1: Sensing and SMA-Actuation Garment

simultaneously collected by a Vicon motion capture system. The results showed that the sensors were able to capture the three shoulder rotations (flexion/ extension, adduction/abduction, and internal/external rotation) with Root Mean Square Error (RMSE) of 3.4 degrees [14].

In this prototype, five SMA actuators, covered with 3.18 mm (1/8") diameter braids (Techflex Flexo PET) were integrated into the garment. While the braids were effective in electrothermally insulating the actuators, they generated significant counter-forces against the actuation direction. The SMA actuators were attached using 9.5 mm (3/8") metallic snaps and placed 2.54cm apart to allow for quick swapping of actuator/braid types while also allowing design explorations/assessment. The actuators were connected to an external power supply in a parallel circuit configuration, allowing each SMA to be controlled separately, therefore generating variable force amounts if needed. However, this requires separate, controllable power sources for each actuator channel. When a set of parallel SMAs are all powered from the same source, overheating or underheating the actuators can occur due variability in the resistance of each actuator.

3.2 Generation 3: Fully-Integrated Soft Sensor-Actuator System

Using the experiences gained from the first generation, we developed a final hybrid soft exoskeleton design, integrating the soft strain sensors and the two types of soft actuators (SMA and pneumatic bladder). The second prototype was fabricated modularly, consisting of a sensing shirt, SMA actuator harness, and the bladder housing unit. The sensing and actuation components were developed with a focus on both wearability and functionality. The sensing shirt has 14 strain sensors distributed around the shoulder joint. A piece of stretchable elastic fabric was sewn on top of each strain sensor for electrical insulation (Figure 4 (a)).

A magnetic fast closing plastic zipper (ANKHGEAR MagZip) was provided in the middle of the garment to enable ease of donning/doffing for users with immobility issues. Unlike the sensing shirt, the actuation layer was made from a non-stretchable fabric (100% polyester plain weave). 10 metallic snaps, spaced 2 cm apart, were placed on each side of the garment in a two-column formation with 4 cm between columns (Figure 2, and Figure 4 (b)). The two-column configuration enables having multiple SMAs in a compact space. An adjustable armband was also designed to anchor the lateral ends of the SMA actuators. To accommodate user anthropometric variability, the armband was designed such that it could be placed on the desired location on the arm and fastened using hook-and-loop fasteners.

To resolve the previously-discussed issue of counter forces, in the second generation of the garment, the PET braids were replaced by softer, more flexible fabric braids. However, the thermal insulation of the fabric braids was lower than the PET braids. The SMA actuators had a length of 24.13 cm (9.5"), and were connected in series in order to heat each of the actuators evenly. Another significant improvement in this design was the integration of the pneumatic actuator (air bladder) for vertical adduction/abduction of the arm. As discussed earlier, the bladder was placed under the armpit to support the arm while SMAs were used to horizontally flex/extend the arm. One side of the pneumatic actuator was fixed on the arm using a non-stretchable strap while the other side was attached to the

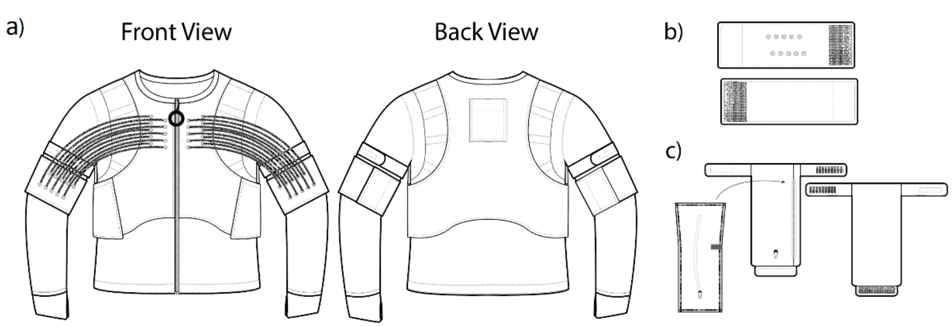

Figure 2. Technical sketches showing (a) the front and back view of the soft exoskeleton system (v2), (b) adjustable arm bands with snapping SMA distal endpoint connections, and (c) pneumatic bladder and housing unit

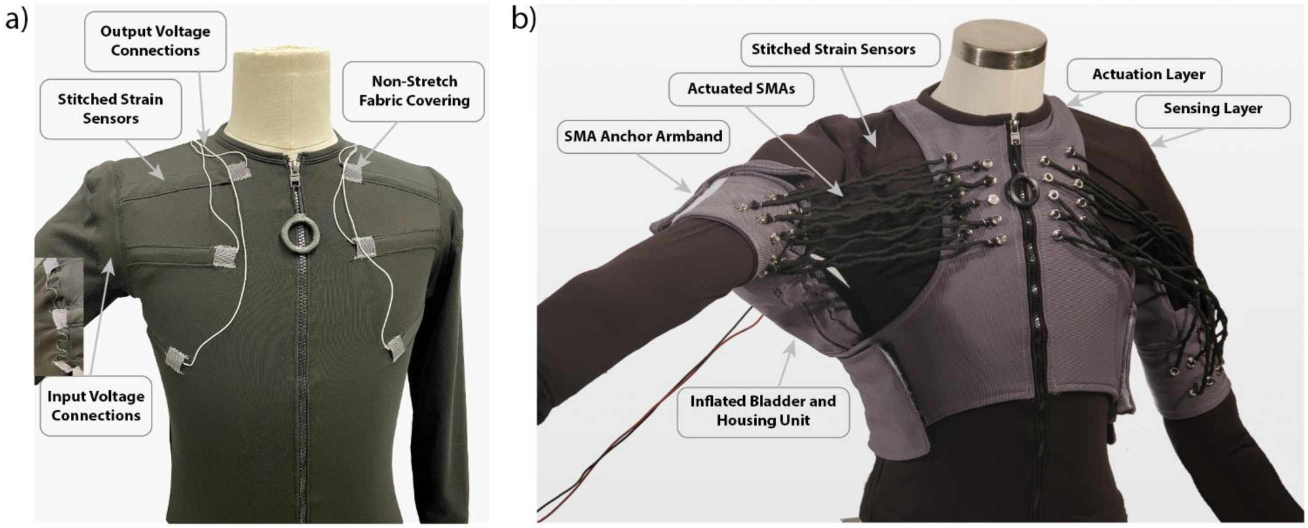

Figure 4. Generation 2: (a) Sensing layer and (b) and the actual Hybrid SMA-Pneumatic Garment

Figure 5. Actuation steps: (from left to right) (1) fully deactivated actuators, (2) partial bladder actuation, (3) partial bladder and SMA actuation, and (4) partial bladder and full SMA actuation

actuation jacket. As demonstrated in Figure 5 the final hybrid exoskeleton prototype system was tested on a mannequin with a biomechanical arm. The arm weighed 1.2 kg and had a length of 62 cm, with the mass center located at 39 cm from the wrist.The designed soft exoskeleton is capable of moving the shoulder in order to follow the desired trajectory by means of hybrid actuation on this biomechanical mannequin.

4 Conclusion

In this paper we discussed the iterative design and development of a novel soft exoskeleton to assist in shoulder abduction/abduction and horizontal flexion/ extension movements, with embedded soft strain sensing to track shoulder joint motion. Two generations of this exoskeleton garment were developed. There remain limitations with the last generation of the prototype that can be improved in further generations of the soft exoskeleton. For instance, the final design still accommodates the weight and bulk of the pneumatic inflatable bladders. Also, as previously discussed, compared to the PET braids, the thermal insulation of the fabric braids is not good enough to protect the skin against the SMA temperature when it is fully activated. Future work will aim to address these challenges and further improve wearability and functionality of the exoskeleton garment. In addition, further experiments are required to fully evaluate the system performance.

ACKNOWLEDGMENTS

The authors would like to thank Esther Foo, Walter Lee, Ellen Dupler, and Miles Priebe. This work was supported by the US National Science Foundation under grants #1722738, #1722540, and #1722596.

REFERENCES

[1] Hassanin Al-Fahaam, Steve Davis, and Samia Nefti-Meziani. 2018. The design and mathematical modelling of novel extensor bending pneumatic artificial muscles (EBPAMs) for soft exoskeletons. *Rob. Auton. Syst.* (2018). DOI:https://doi.org/10.1016/j.robot.2017.10.010

[2] Matteo Cianchetti, Cecilia Laschi, Arianna Menciassi, and Paolo Dario. 2018. Biomedical applications of soft robotics. *Nature Reviews Materials*. DOI:https://doi.org/10.1038/s41578-018-0022-y

[3] Dorin Copaci, Enrique Cano, Luis Moreno, and Dolores Blanco. 2017. New Design of a Soft Robotics Wearable Elbow Exoskeleton Based on Shape Memory Alloy Wire Actuators. *Appl. Bionics Biomech.* (2017). DOI:https://doi.org/10.1155/2017/1605101

[4] Dorin Copaci, Fernando Martin, Luis Moreno, and Dolores Blanco. 2019. SMA Based Elbow Exoskeleton for Rehabilitation Therapy and Patient Evaluation. *IEEE Access* (2019). DOI:https://doi.org/10.1109/ACCESS.2019.2902939

[5] Guido Gioberto, James Coughlin, Kaila Bibeau, and Lucy E. Dunne. 2013. Detecting bends and fabric folds using stitched sensors. In *Proceedings of the 17th annual international symposium on International symposium on wearable computers - ISWC '13*, ACM Press,

New York, New York, USA, 53. DOI:https://doi.org/10.1145/2493988.2494355

[6] Alireza Golgouneh, Brad Holschuh, and Lucy Dunne. 2020. A Controllable Biomimetic SMA-actuated Robotic Arm. In *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics*, 152–157. DOI:https://doi.org/10.1109/BioRob49111.2020.9224371

[7] Alireza Golgouneh, Jiaqi Li, Julianna Abel, and Lucy Dunne. 2021. A Smart Controllable SMA-Based Tourniquet. In *Proceedings of the ASME 2021 Conference on Smart Materials, Adaptive Structures and Intelligent Systems (SMASIS2021)*, American Society of Mechanical Engineers.

[8] Alireza Golgouneh, Md Tahmidul Islam Molla, and Lucy E. Dunne. 2019. A comparative feasibility analysis for sensing swelling with textile-based soft strain sensors. In *Proceedings - International Symposium on Wearable Computers, ISWC*. DOI:https://doi.org/10.1145/3341163.3347739

[9] Neal Halfon, Amy Houtrow, Kandyce Larson, and Paul W. Newacheck. 2012. The changing landscape of disability in childhood. *Futur. Child.* (2012). DOI:https://doi.org/10.1353/foc.2012.0004

[10] Bai Li, Huantian Cao, Ben Greenspan, and Michele A Lobo. 2021. Development and evaluation of pneumatic actuators for pediatric upper extremity rehabilitation devices. *J. Text. Inst.* (2021), 1–8.

[11] Bai Li, Ben Greenspan, Thomas Mascitelli, Michael Raccuglia, Kayleigh Denner, Raymond Duda, and Michele A. Lobo. 2019. Design of the Playskin Airtm: A user-controlled, soft pneumatic exoskeleton. In *Frontiers in Biomedical Devices, BIOMED - 2019 Design of Medical Devices Conference, DMD 2019*. DOI:https://doi.org/10.1115/DMD2019-3231

[12] Michele A. Lobo and Bai Li. Feasibility and effectiveness of a soft exoskeleton for pediatric rehabilitation. In *The International Symposium on Wearable Robotics (WeRob2020) AND Wearracon Europe*.

[13] Christian Di Natali, Ali Sadeghi, Alessio Mondini, Eliza Bottenberg, Bernard Hartigan, Adam De Eyto, Leonard O'Sullivan, Eduardo Rocon, Konrad Stadler, Barbara Mazzolai, Darwin G. Caldwell, and Jesús Ortiz. 2020. Pneumatic Quasi-Passive Actuation for Soft Assistive Lower Limbs Exoskeleton. *Front. Neurorobot.* (2020). DOI:https://doi.org/10.3389/fnbot.2020.00031

[14] Amanda Jean Redhouse. 2021. Joint Angle Estimation Method for Wearable Human Motion Capture. Virginia Tech. Retrieved from http://hdl.handle.net/10919/103629

[15] Conor J Walsh, Ciaran O'Neill, and Nathan Phipps. 2020. Textile Actuators. Retrieved from https://patents.google.com/patent/US20200170873A1/en

[16] Centers for Disease Control: FastStats.