Self-Tightening and Self-Fastening Belts and Shoes: Shape Memory Adaptive Apparel to Assist Individuals with Physical Limitations

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ABSTRACT

People with physical disabilities face significant challenges in basic activities like dressing and undressing. The CDC reports that 3.6% of U.S. adults have self-care disabilities impacting dressing or bathing. Adaptive clothing, designed to facilitate dressing, includes features such as zip-off sleeves, Velcro shoes, and side-opening pants, which enhance autonomy and quality of life. Current adaptive shoes primarily use Velcro straps and wide openings with zippers. We seek to expand the adaptive clothing solution space by exploring garment-based soft robotics, such as shape memory alloy (SMA) springs, to offer advanced solutions. In this study, we developed and tested self-tightening and self-fastening belts and shoes using SMA actuators as tightening mechanisms and both hook-and-eye and electromagnetic components as fastening solutions, to improve accessibility and independence for individuals with physical limitations.

CCS CONCEPTS

• hardware - emerging technologies – analysis and design of emerging devices and systems • human centered computing - human-computer interaction - interaction devices

KEYWORDS

Adaptive Clothing, Device Design, Wearable Technology, Shape Memory Actuators, Soft Robotics

ACM Reference format:

Xin-Ting Liu, Heidi Woelfle, and Brad Holschuh. 2024. Self-Tightening and Self-Fastening Belts and Shoes: Shape Memory Adaptive Apparel to Assist Individuals with Physical Limitations. In *Companion of the 2024 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp Companion '24), October 5–9, 2024, Melbourne, VIC, Australia.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3675094.3681948

1 INTRODUCTION

People with physical disabilities may have serious challenges when it comes to basic activities such as dressing and undressing [1]. According to Centers for Diseases Control and Prevention, 3.6 percent of U.S. adults have a self-care disability with difficulty dressing or bathing [2]. Adaptive clothing refers to garments that are specifically designed to facilitate dressing for individuals who face challenges in this task [3]. Individuals who struggle to dress independently and effortlessly may find adaptive clothes highly beneficial. Several adaptive designs have been made to traditional clothing styles, including zip-off sleeves, shoes with Velcro, closures on the back, front-opening bras, and side-opening pants. The modification of clothing can greatly enhance an individual's quality of life, granting them the autonomy to dress independently. Individuals with physical limitations may have challenges when it comes to handling fasteners like buttons, zippers, and hooks, which can be particularly demanding. A lack of adapted clothes or apparel for people with disabilities can be a barrier to participation in meaningful activities [4].

This study concentrates on the design of adaptive belts and shoes, which many individuals must wear every day. The functional ability to wear shoes encompasses several factors that enable an individual to independently and effectively put on and take off footwear. Dexterity, muscle strength, and range of motion are all important physical characteristics that are required when putting on and taking off shoes or tightening / fastening belts. Insufficient functional abilities can result in difficult donning and doffing shoes for individuals with limitations. Many adaptive shoes that are currently on the market utilize Velcro as their fastener because it requires less dexterity to fasten than traditional shoelaces. Some adaptive shoes have wraparound zippers with a wide opening on the side or top of the shoe, making it easier for an individual to

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UbiComp Companion '24, October 5–9, 2024, Melbourne, VIC, Australia

ACM ISBN 979-8-4007-1058-2/24/10.
https://doi.org/10.1145/3675094.3681948

don the shoe and the ability to accommodate orthotics. However, all these solutions still require some amount of dexterity and strength in order to be donned or doffed without assistance. In this case, garment-based soft robotics is an emerging domain which seeks to integrate compliant mechanical actuators into textile/clothing form factors to achieve autonomous functions, which could prove especially useful as accessibility solutions if designed to support tightening or fastening of everyday garments [5, 6].

In this study, we develop and test an initial suite of garment-based technologies to overcome accessibility challenges in everyday clothing, encompassing a set of adaptive solutions that can support and assist with the daily challenge of tightening/loosening or fastening/unfastening a garment. Shape memory alloy (SMA) springs have the potential to be used as self-tightening mechanisms for adaptive clothing. SMA springs are actuator structures that constrict when heated (either by an electric current or through direct applied heat), and function like an artificial muscle that can be integrated directly into wearable systems [7]. SMA-based wearables are widely used in exoskeletons and textiles for rehabilitative or protection purposes [8, 9]. Here, we present two novel garment-based soft robotic systems / solutions: (1) a self-tightening belt using SMA actuators and hook-and-eye fasteners, and (2) self-tightening shoes using SMA actuators and multiple fastening structures (hook-and-eye and electromagnets), to demonstrate the viability of garment-based soft robotic technologies as accessibility solutions.

2 DEVICE DESIGN

We developed two embodiments of self-tightening / self-fastening wearable systems, each of which utilize SMA springs as tightening mechanisms and either traditional (i.e., hook-and-eye) or advanced (i.e., electromagnetic) fastening mechanisms, and then integrated these systems into different types of garments (i.e., belts and shoes) through a series of prototype iterations.

2.1 Design Criteria

Individuals with disabilities often face unique challenges when it comes to donning, doffing, and managing closures on clothing and footwear. These difficulties can vary widely depending on the nature and extent of the disability. For the individuals with mobility impairments, they may have limited range of motion to manipulate clothing and closure, weak grip strength, or a lack of coordination to deal with buttons and tying shoelaces. With the self-tightening design, the challenges of reach, dexterity and mobility can be minimized with simple operation to (e.g. push on/off button to activate tightening or release) automatically activate the process of tightening and fastening. By utilizing the mechanical features of SMA springs which they can be electrically controlled through Joule heating, the tasks require reach, dexterity, and mobility, such as tying shoelace or fastening the belt, can be finished based on the advantages of the SMA actuation.

2.2 Device Development and Early Prototypes

2.2.1 Self-tightening Belt.

The self-tightening belt – shown in Figure 1 -- was created using a shape memory alloy (SMA) actuator and a hook-and-eye fastening structure, allowing it to automatically tighten and fasten without any manual operation. In this architecture, coiled SMA wire (Dynalloy Flexinol 70°C, 0.12” diameter) was the core actuation component, actuating with applied current to tighten the belt structure [7]. The cinch-style belt combined with the leather belt and Velcro strap can provide a stable base for smoothing the sliding movement of the belt during the self-tightening phase. SMA spring was used to combine with an inextensible cinch-style belt, outfitted with traditional hook-and-eye closures along its length. The SMA spring was attached to snap both the free end and cinch loop of the belt, such that when the SMA spring contracts linearly it tightens the cinch. Teflon is utilized as a layer to isolate SMA from the fabrics beneath where the SMA spring is located, for the purpose of preventing the fabrics from melting during the heating process. The free end of the belt is outfitted with a hook component on its inner surface, and eye components are spaced regularly along the belt length such that when the belt is pulled by the SMA springs, the hook and eye components are pulled into alignment (see Figure 2). This architecture offers an automatic, adjustable tightening and fastening capability that can be sustained without continuous power.

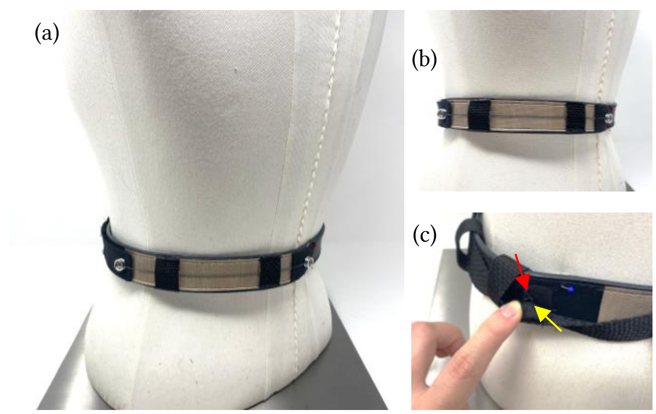

Figure 1: (a) The architecture of the self-tightening belt. (b) use snap buttons to fix and connect the SMA spring. (c) hook-and-eye latching mechanism. The yellow arrow indicates the hook component, while the red arrows indicate the eyes components.

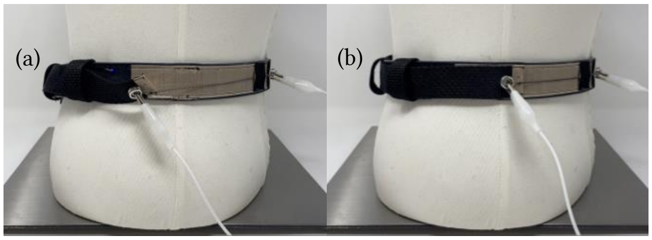

Figure 2: The time-lapse of self-tightening belt. (a) pre-actuation (b) during fastening.

2.2.2 Self-tightening Shoes.

Two versions of self-tightening shoes were developed and tested: the first adopted the same hook-and-eye architecture as the self-tightening belt to form the closure, whereas the second implemented a powered electromagnetic fastener as an alternative embodiment. The self-tightening process is accomplished by utilizing the contraction of the SMA spring to pull the two ends of the shoelaces, resulting in a tight fit (see Figure 3). The hook-and-eye closures were implemented to enable adjustable tightness. We attached the snaps to the two ends of the shoelaces, each on its own end, and then affixed a single hook component to the inner side of both snaps. The multiple eye components were spaced regularly around the heel contour. Purposefully-engineered channels were established to ensure that the movement of the shoelace pulled by the SMA contraction was in alignment with the eye components.

After connecting to the power supply, the SMA spring contracts, and pulls both ends of the shoelaces, drawing the two sides of the quarters closer and tighter. During the contraction of the SMA spring, the hook situated on the inner side of the snap latches with one of the eye components positioned around the contour (see Figure 4).

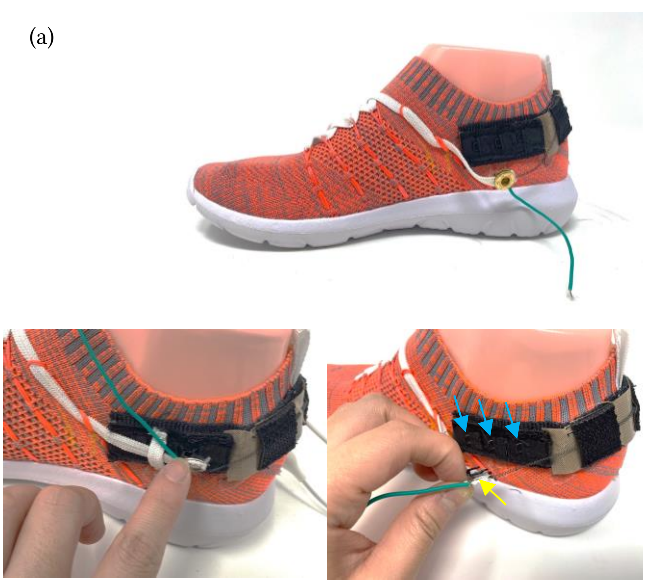

Figure 3: (a) The prototype of the self-tightening shoe with hook-and-eye architecture to form the closure. (b) the fastening system. Snap buttons are used to fix and connect the SMA spring. Shoelace can be pulled tight during SMA constriction. (c) the hook-and-eye latching mechanism. The yellow arrow indicates the hook component, while the blue arrows indicate the eyes components.

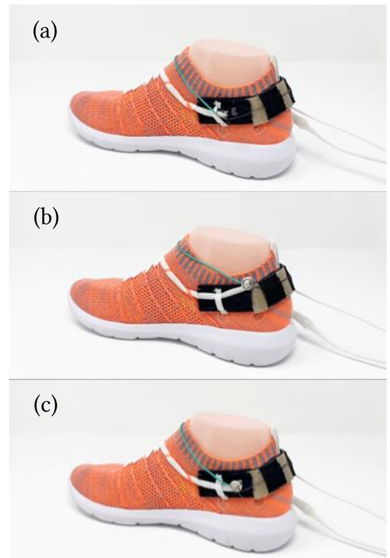

Figure 4: The time-lapse of self-tightening shoe with hook-and-eye architecture to form the closure. (a) pre-actuation (b) during actuation (c) during fastening.

The second iteration of the self-tightening shoe uses electromagnets for fastening (see Figure 5). In this second iteration, we also implemented a side-opening design (a typical feature in commercially-available adaptive shoes), which may make donning easier for some individuals. The fastening architecture is composed of one customized leather strap and one elastic band. At each end of the leather strap, there is a hole that serves as channels for the elastic band to pass through. The leather strap can become a solid base to avoid unwanted wrinkles on the shoe's surface, which could interfere with the sliding movement of the elastic band and make the latching fail. Two reconfigurable SMA springs were incorporated onto a wide elastic across a commercially available slip-on shoe (STQ Slip On Sneakers), and the actuators can be electrically controlled through Joule heating via current delivered through snap fixtures. When in use, the actuators are powered individually. An electromagnet was also embedded in the elastic band, which when powered is attracted to a passive magnet mounted to the tongue of the shoe.

Figure 5: (a) The self-tightening shoe prototype incorporates an electromagnet for fastening. (b) the fastening system. The constriction of multiple SMA springs can pull the elastic band tight, forming the closure. (c) the electromagnetic latching mechanism. The red arrow indicates the electromagnet, while the yellow arrow indicates the passive magnet.

During the electromagnet's power-up phase, a magnetic force of attraction was generated and intensified, securing the latching with the passive magnet on the shoe tongue, and. remained securely attached even after power was removed. This allowed the shoe to be permanently fastened without requiring constant power.

While this embodiment demonstrates one strategy for magnetic latching (via a powered electromagnet), the architecture could be reworked to include either 1) a passive magnet on the elastic strap (to provide permanent and passive attachment once aligned with the passive magnet in the shoe tongue), or 2) an electropermanent magnet on the elastic strap that affords unpowered attachment and powered detachment. These design options could be easily achieved through simple modification to the existing prototype, and offer a variety of functional characteristics depending on the needs or desires of the wearer.

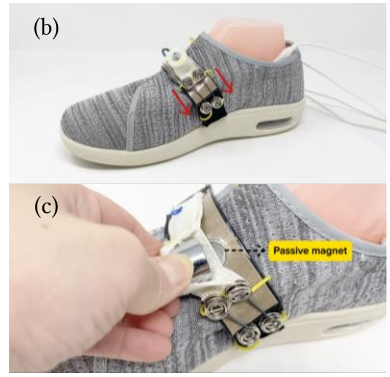

Figure 6: The time-lapse of self-tightening shoe incorporates an electromagnet for fastening. (a) pre-actuation (b) during actuation (c) during fastening.

3 CONCLUSION

Comparing the hook-and-eye and electromagnetic fastening mechanisms, we found that the electromagnetic mechanism proved more reliable at fastening because it did not require as precise of alignment between the fastening components (i.e., the hook-and-eye only fastens when the hook and eye are precisely aligned, whereas the electromagnet fastens anytime the permanent magnet and electromagnet are within their local area of magnetic attraction). Additionally, using the electromagnet as the fastener could enhance the autonomous ability of our adaptive device, as we can actively unfasten as well by inverting the current (to produce a repelling force rather than an attractive force).

Overall, both embodiments (belt and shoe) and both fastening strategies (hook-and-eye and electromagnet) combined with SMA spring actuators proved capable of providing both self-tightening and self-fastening functionality in everyday clothing form factors. With these garment-based soft robotic solutions, we aim to enhance autonomy and ease of use for individuals who struggle with clothing accessibility challenges, and in doing so, seek to enable greater independence and improved daily living for individuals with physical limitations.

ACKNOWLEDGMENTS

The authors would like to thank our collaborators at University of Delaware – Dr. Michele Lobo, Tamara Wright, and Sarah Megivern. This work is supported by the National Science Foundation (grant #2324342).

REFERENCES

[1] Aguiar, G.C., et al. Fashion and Inclusive Design: Assistive Technologies Applied to Clothing. in Advances in Industrial Design: Proceedings of the AHFE 2020 Virtual Conferences on Design for Inclusion, Affective and Pleasurable Design, Interdisciplinary Practice in Industrial Design, Kansei Engineering, and Human Factors for Apparel and Textile Engineering, July 16–20, 2020, USA. 2020. Springer.

[2] Centers for Disease Control and Prevention. Disability and Health Data System (DHDS). 2023 May; Available from: http://dhds.cdc.gov.

[3] Poonia, N., Adaptive clothing for disabled people. International Journal of Home Science, 2020. 6(2): p. 238-241.

[4] Kabel, A., K. McBee-Black, and J. Dimka, Apparel-related participation barriers: ability, adaptation and engagement. Disability and Rehabilitation, 2016. 38(22): p. 2184-2192.

[5] Sanchez, V., C.J. Walsh, and R.J. Wood, Textile Technology for Soft Robotic and Autonomous Garments. Advanced Functional Materials, 2021. 31(6): p. 2008278.

[6] Granberry, R., et al., Functionally graded knitted actuators with NiTi-based Shape Memory Alloys for topographically self-fitting wearables. Advanced materials technologies, 2019. 4(11): p. 1900548.

[7] Holschuh, B., E. Obropta, and D. Newman, Low spring index NiTi coil actuators for use in active compression garments. IEEE/ASME Transactions on Mechatronics, 2014. 20(3): p. 1264-1277.

[8] Srivastava, R., et al., Shape Memory Alloy-Based Wearables: A Review, and Conceptual Frameworks on HCI and HRI in Industry 4.0. Sensors (Basel), 2022. 22(18).

[9] Pettys-Baker, R., H. Woelfle, and B. Holschuh. Robo-Coverstitch: Coverstitched Auxetic Shape Memory Actuators For Soft Wearable Devices. in Proceedings of the 2023 ACM International Symposium on Wearable Computers. 2023.