Soft Ro-bra-tics: Adaptive Bra Design Using Integrated Shape Memory Materials

Heidi Woelfle
Wearable Technology Lab
University of Minnesota
St. Paul, MN, USA
woel0055@umn.edu

Anna Keith
College of Design
University of Minnesota
St. Paul, MN, USA
keith174@umn.edu

Gina Marie Bradford
College of Design
University of Minnesota
St. Paul, MN, USA
bradf185@umn.edu

T-jay Yang
College of Design
University of Minnesota
St. Paul, MN, USA
yang7895@umn.edu

Xin-Ting Liu
Wearable Technology Lab
University of Minnesota
St. Paul, MN, USA
liu02614@umn.edu

Lucy E. Dunne
Wearable Technology Lab
University of Minnesota
St. Paul, MN, USA
ldunne@umn.edu

Brad Holschuh
Wearable Technology Lab
University of Minnesota
St. Paul, MN, USA
bth@umn.edu

Abstract

Garment-based soft robotics is an emerging domain which seeks to integrate compliant mechanical actuators into textile/clothing form factors. There exists a significant opportunity to develop and deploy these garment-based technologies to overcome accessibility challenges in everyday clothing, providing a suite of adaptive solutions that can support and assist with the daily challenge of tightening/loosening or fastening/unfastening a garment. In this paper, we present two embodiments of adaptive bras with embedded shape memory materials to provide robotically-assisted adaptive / customizable fit – one embodiment is designed for individuals with dexterity limitations that are typical in conditions such as arthritis, and another embodiment is designed to be fully usable with one hand. This approach, which we define as "Soft Ro-bra-tics", represents a novel solution to overcome bra-related accessibility issues.

Ccs Concepts

•Hardware~Emerging technologies~Analysis and design of emerging devices and systems •Human-centered computing~Human computer interaction (HCI)~Interaction devices

Keywords

Wearable Technology; Soft Robotics; Shape Memory Materials; Adaptive Clothing, Accessibility Design, Universal Design

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1 Introduction

Individuals with physical impairments can significantly struggle with simple everyday tasks associated with dressing and undressing [1]. Traditional garment structures that are ubiquitously used for fitting/tightening/fastening clothing – e.g., zippers, snaps, buttons, laces, or belts – require varying degrees of physical strength, dexterity, precision, and manual control that may exceed the abilities of individuals with age-related (or other) impairments [2]. Because this is literally an everyday struggle – we must don and doff clothes every day – these challenges can lead to significant impacts in quality of life, independence, and even health/wellness for the affected individual [3]. For example, those with limited flexibility or dexterity may be unable to independently tighten their shoes, which can compromise their ability (and confidence) to leave the house [4], [5]; those who lack the strength to don their medically-necessary compression stockings won't wear them, compromising their treatment and thus, their health [6]; and those who struggle to fasten traditional dress clothes (business shirts, pants, etc.) may instead choose to socially withdraw from scenarios where such attire is expected [7], [8]. These are real threats to individual health and autonomy, which require us to rethink traditional approaches to apparel design and to look for opportunities to leverage technology for novel accessibility solutions.

2 Bra Accessibility Issues & Market Gap

McBee-Black et al. surveyed 54 female and non-binary people with disabilities about their satisfaction and challenges with intimate apparel. 69.61% of respondents expressed dissatisfaction with the ease of wearing bras, and 66.67% were dissatisfied with the assortment/selection of bras. Fastening the closures was the number one challenge reported with wearing bras, followed by donning, difficulty of using straps, uncomfortable fabric, doffing, a fit that is too tight, and a fit that is too loose. When combining the responses for a fit that is too tight or too loose, fit becomes the number one challenge identified by respondents [9].

To identify gaps in the adaptive bra market, we collected product information on adaptive bras currently available for purchase online. We included bras that were labeled or advertised as being adaptive and also included bras that were recommended in disability or bra fitting community forums. For each bra identified, we collected information on price, type (underwire vs. wireless), size range, number of colorways, material content, closure type and location, methods of adjustment for both the band and straps, and whether the bra contained assistive dressing loops.

We identified 72 unique bra styles made by 21 different brands. 77% of the bras were wireless while 23% contained underwire. Closure types varied greatly and included zippers, hook and eyes, magnets, clasps, Velcro, and snaps. Clasps were the most common closure (24%) followed by hook and eyes (19%). All of the bras' closures were located at either the center front (88%), off-center (7%), or side (4%). 1 bra had no closure at all, as it is doffed by pulling it over the head. 80% of the bras had no way of adjusting the dimensions of the bra band. 7% of the bras contained hook and eyes in the back of the bra that would need to be fastened before doffing, while the remaining 13% could be adjusted in the front with a clasp, hook and eyes, or Velcro. 55% of bras used sliders to adjust the length of the straps, while 32% had no way of adjusting the straps at all. Of the bras that used sliders for strap adjustment, 60% had those sliders placed at the back of the straps and 40% had them placed in the front.

The lack of adjustability in bra bands may be a contributing factor to the large number of fit challenges reported in the survey by McBee-Black et al. Though these bands usually contain elastic to aid in fitting, the wearer has no control over how loose or tight the elastic is, and the presence of elastic and negative ease in the band may make fastening the closures more difficult for people with limited strength. Some of the closure types, though placed in a more convenient location at the front of the bra, still require fine motor skills and good vision to fasten them. Though there were a wide variety of closure types identified in adaptive bras, it's clear from the responses to the McBee-Black et al. survey that the currently available closures are not meeting the needs of many people with disabilities.

We found only 7 adaptive bras that could be donned with the use of only one hand, 4 of which were wireless and 3 which contained underwire. Wireless bras are preferred by some but lack enough support for others. The one-handed underwire bras are required to be donned over the head, which may not be feasible for everyone.

Based on these findings, we developed the following design criteria for future adaptive bras:

- The bras should have a closure that is easy to use.
- There should be adjustability in the fit.
- The straps should be simple to wear and use.
- Comfort should be prioritized whenever possible.
- The bras should differentiate from what is currently available on the market.

3 *Soft Ro-bra-tics*: Soft Robotic Adaptive Bras using Shape Memory Materials

While passive solutions are the most common form of adaptive clothing on the market today, there have been limited commercial efforts to introduce *powered* technologies to create active accessibility solutions. Nike introduced the Nike MAG proof of concept in 2016 (inspired by Back to the Future) which offered self-tightening functionality (i.e., adaptive lacing) in the shoes using embedded cable/motor systems. We expand on this approach by exploring adaptive bra design using *shape memory materials*, specifically shape memory alloys (SMAs), which are metals that exhibit thermally-induced shape change that can be specifically engineered to create tightening effects in everyday clothing. [10], [11], [12] By combining SMA structures (for dynamic fit) and traditional fasteners (e.g., buckles designed for one-handed use) we can create a new paradigm for accessible bra design which we define as S*oft Ro-bra-tics.* This novel approach to bra accessibility design allows for a vastly improved user experience, including:

1) Ease of donning, because the garment can be initially oversized
2) Ease of fastening, because the fastening step can occur *before* the tightening step (minimizing the strength / dexterity required of the wearer)
3) Customized fitting / tightening, because the embedded SMA actuators can dynamically tighten the band and/or straps to perfectly accommodate each wearer

We explore this approach in the following two case studies.

3.1 SMA Adaptive Bra for Arthritic Users

Individuals with arthritis can significantly struggle with simple everyday tasks associated with dressing and undressing. Arthritic women specifically find bras to be one of the most difficult garments to don and doff. [13] To design an adaptive bra for arthritic users using SMA actuators, several design factors related to buckle design, buckle placement, and user strength/dexterity were first investigated.

3.1.1 Strength and Dexterity Evaluation: No published data could be found regarding arthritic strength, dexterity, and mobility and the use of buckles whereas a great number of studies had been conducted on other closures. Buckles were chosen as they are typically a one step process, require less precise dexterity, and come in a number of different forms. To understand directional strength of arthritic women a test was conducted with a minimum of 5 participants to a maximum of 15 total participants for each category within the test. Participants donned a heavy winter glove on their right hand to simulate the feeling of having arthritis. Utilizing a luggage scale to test directional strength, participants held the luggage scale in their left hand and using their right hand with the heavy winter glove on, in a pinch like manner, pulled on the weight scale reader. The proximal pinch grip strength was greater in the anterior median of the body compared to posterior with an average strength of 8.35 lbs. Based on these tests, it was determined that any pulling done during fastening should involve a proximal pinch grip in the anterior median of the body, as participants in this category experienced the most strength in comparison to the proximal pull posterior median of the body.

3.1.2 Fastener Location Evaluation: To understand the optimal location for the closure of the bra in relation to arthritic women with physical impairments, a test was conducted with 5 female participants who were timed donning and doffing the bra using three different closure locations: anterior, posterior and side. The participants also wore winter gloves that were used to simulate arthritis. The results of this test were that the anterior location was the most optimal for the impairments resulting from arthritis.

3.1.3 Optimal Buckle Design Assessment: We analyzed four different buckle designs and how people with simulated arthritis gloves performed with them and reacted to using them. The four buckles analyzed include the Sacoora Breakaway Buckle, Coobigo Quick Release Buckle, YKK Center Button Buckle, and the Coobigo Side Release Buckle. Don and doff times were taken as well as participants' confidence levels and scoring of all four buckles. The YKK Buckle was rated best in both confidence and overall rating, and required the least amount of don and doff time. Don time seemed to matter less than doff time to participants when considering confidence and overall rating.

3.1.4 Design Concept: The final design is shown in Figure 1, and utilizes a YKK Center Button Buckle at the center-front of the bra. To enable soft robotic fit adjustment, the bra contains two mesh panels on either side of the bra containing four SMA spring actuators each. The SMAs allow the bra to be "oversized" before donning, and subsequently actuated to tighten after donning. Once the bra is donned and fastened, the SMA springs can be heated to generate a linear contraction of the mesh panel (via either equilibration to body temperature or through externally applied heat / electricity, tightening the bra and fitting it to the body.

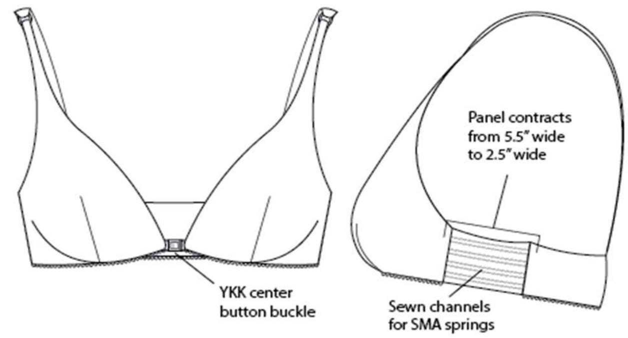

Figure 1: Adaptive bra design for arthritic users

3.1.5 Prototype and Construction Method: The SMA bra prototype was manufactured using Dynalloy Flexinol 70C SMA springs, a YKK Center Button Buckle, a Cotton Jersey Knit fabric and Nylon + Spandex Mesh fabric. Channels for each of the SMA springs were created by topstitching on two layers of mesh fabric, used to create each of the side panels. The springs are attached by looping around a metal eye at each end of each channel. The buckle is attached to an elastic band that provides under bust support for the wearer and extends around the circumference of the bra. The final prototype can be seen in Figure 2.

Figure 2: Adaptive bra prototype for arthritic users

3.2 SMA Adaptive Bra for One-Handed Use

The only one-handed underwire bras we found in our market survey were all donned over the head and fastened at the wearer's side. Because of this, we sought to design a SMA-assisted, one-handed underwire bra which could be fastened in the front.

3.2.1 Closure Selection: We evaluated several different off-the-shelf one-handed fasteners for their potential for inclusion in our bra prototype: a magnetic snap buckle (Fidlock), a magnetic hook (Fidlock) and nursing clips in three sizes (3/8", 1/2", 5/8") The fasteners from Fidlock were eliminated from consideration due to their form factors which were too large and bulky for use in a bra. We chose the 5/8” size nursing clip over the 3/8” and 1/2” sizes because we found it required the least amount of dexterity to fasten at a size that was still appropriate for inclusion at the center-front of the bra between the cups. Smaller hook and eyes may present challenges for some people with disabilities, however, nursing clips contain hooks that are significantly larger and are designed to be fastened and unfastened with only a single hand. Though these clips are typically used to connect the cup of a nursing bra to the strap, we found that when placing one horizontally at the center of a bra it could still be fastened with one hand but that doing so was easier when the band is oversized.

3.2.2 Ease Evaluation: To determine how much ease was needed to fasten the closure easily with one hand, we added extension panels to the center back of the bra in half inch increments until one of the researchers was able to fasten the closure with ease. We found that for the researcher, who is able-bodied, 3” of ease was the minimum amount needed to easily fasten the closure. We determined that the ease should be distributed between the sides and the back of the bra, rather than all at the back, so that the straps do not slide off the arm while donning. With the goal of accommodating as many individuals as possible, we chose to add a total of 6” of ease to the band.

3.2.3 Design Concept: Our bra design, shown in Figure 3, has 6” of added ease distributed between three panels: one at each of the sides and one at the center back of the bra. Each side panel contains 4 SMA springs and expands by 1.5”. The back panel contains 2 SMA springs and expands by 3”. The bra straps can also be adjusted by a total of 1.875” using a single SMA spring.

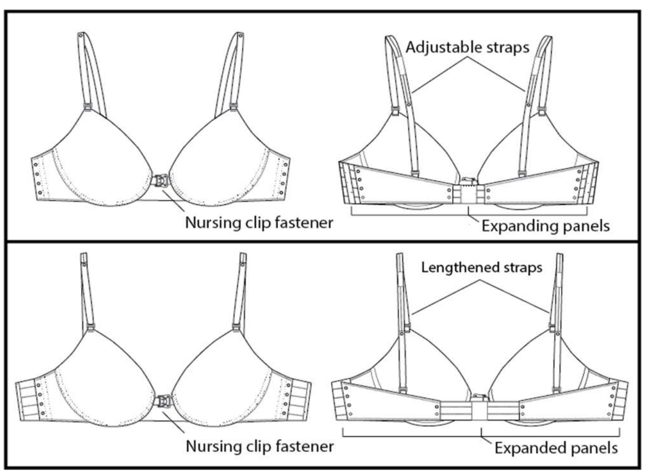

Figure 3: Adaptive bra design for one-handed use. Contracted view (top) and expanded view (bottom)

3.2.4 Prototype and Construction Method: The band is constructed of two layers of a nylon spandex blend fabric, adhered together using a fusible adhesive (Heat-n-Bond Soft Stretch). The SMA springs, made using Dynalloy Flexinol 70C wire, were attached to the bra using rivets, which were chosen as a fastener for their small size and low profile. At each of the panels, the SMAs contract and pull the outer layer over the inner layer so that they overlap. Teflon was adhered to the outside of the inner layer at these locations so that the SMA springs and outer layer could glide smoothly without causing the fabric to buckle or bunch. The strap is looped through a plastic slider at the front and back of the bra where it overlaps itself. The two ends of the strap are connected to a single SMA spring attached with rivets. To maximize comfort in this complex design, the number of seams and amount of stitching were reduced as much as possible [14]. The band contains only 3 seams: 2 where the band is connected to the molded cups (which have a seam covering typical of underwire bras), and the third located at center back. The center back seam was only necessary due to limitations in fabric width. A fusible adhesive was utilized to join the inner and outer layers, reducing the need for stitching and preventing fabric bunching. Before donning the bra, the panels and straps are manually expanded by pulling each of them apart. Then, each bra strap is donned by pulling it over each of the arms. After that, the two cups are pulled together using a single hand and the nursing clip is fastened. Heat is then applied to the SMA springs (either via equilibration to body heat or through externally applied heat / electricity) to contract them until the desired dimension is reached. The final prototype is shown in Figure 4.

Figure 4: Adaptive bra prototype for one-handed use

4 Conclusion

These prototypes address the unique challenges faced by people who struggle with bra accessibility. The designs significantly reduce the strength and dexterity required to don each bra, by utilizing embedded SMAs to perform tightening / fitting *after the bra is already donned and the center closure is fastened.* These prototypes offer the potential for greater independence and comfort for people with bra-related accessibility challenges.

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