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DESIGN TRADEOFFS IN THE DEVELOPMENT OF A WEARABLE SOFT EXOSKELETON FOR UPPER LIMB MOBILITY DISORDERS

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ABSTRACT

This paper investigates the tradeoffs between design variables important for the development of a mobility support soft exoskeleton for horizontal shoulder adduction. The soft exoskeleton utilizes discreet shape memory alloy (SMA) spring actuators to generate the required torque to move the arm segment, while preserving the qualities of a soft, wearable garment solution. A pilot benchtop test involving varying power input, actuator anchor position, actuator orientation, and added weight, was investigated to evaluate their effects against the degree of motion the soft exoskeleton allows. The results show that the power input, actuator anchor position, and simulated limb weight each affect the ultimate horizontal adduction angle the exoskeleton is able to induce. Further, the project highlights a crucial point in regard to the tradeoffs between functionality and wearability: when actuator orientation was investigated, we found a decrement in functionality (as measured by maximum achievable horizontal adduction angle) when the actuators were constrained close to the body. This shows that when aiming to improve the hypothetical system's wearability/usability, the effective torque that can be generated is reduced. Together these findings demonstrate important design considerations while developing a wearable, soft exoskeleton system that is capable of effectively supporting movement of the body while maintaining the comfort and discreetness of a regular garment.

Keywords: Soft Exoskeleton, Soft Robotics, Wearable Technology, Shape Memory Alloys

INTRODUCTION

Mobility impairments affect millions of people in the world across all life stages. Childhood mobility impairment is an important platform for developing technological interventions for two reasons: (1) the benefits are far-reaching since extremity function is important for exploration and learning during the early developmental years [1, 2], and (2) the supporting forces required to manipulate children's bodies are smaller. This project investigates the parameters associated with the development of an upper extremity, active wearable soft robotic system to support upper limb movements, specifically shoulder horizontal adduction, with an overarching goal of developing systems to support children with mobility impairments.

Prior work in mobility-support exoskeletons have used various actuation mechanisms [3–5], including pneumatics [6], [7], electromagnetics [8], or hydraulics [9]. Traditional exoskeleton actuation schemes, while providing good power-to-weight ratio and having high efficiencies and control, typically come in form factors that are relatively large and rigid, hence limited in wearability. Wearability is defined as the 'interaction between the human body and the wearable object' [10], and in this context, refers to the 'degree of comfort (physical, mental, emotional, and social) afforded by a body-mounted object or device [11]. Some design guidelines for wearability proposed by Gemperle et. al. (1998) include considerations of placement, weight, human movement, attachment, accessibility, and long term use, just to name a few [10]. To overcome the limitations in wearability of traditional exoskeleton systems, soft robotics (i.e., actuated systems that utilize non-rigid materials) are an appealing alternative solution that balance functionality and wearability since they typically come in form factors that are less rigid and much more compliant to the body.

However, wearable soft robotic systems have to overcome several major challenges to effectively support or manipulate the body, including (1) generating sufficient force/torque to move a targeted body part, (2) anchoring the system to the body for leverage during actuation, and (3) applying a force vector while preserving mobility. This project utilizes shape memory alloy

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(SMA) actuators, which are a type of active material that is common to soft robotics and has great potential for use in exoskeleton applications. SMAs have the ability to transform into a pre-trained shape when heated (i.e., can be controlled with an applied current through Joule heating) [12], which we will be leveraging to achieve sustainable body segment movements. Prior work has seen the use of SMA actuators to produce movement on the body, but they are typically coupled with rigid structures and the use of them in a wire configuration may not truly maximize their afforded potential [13–16]. Here, we form the SMA wires into small diameter springs that constrict when heated (such that they serve as linear actuators) and couple them with traditional textile structures to produce soft exoskeletons that are both functional, discreet, and wearable. The actuators in this study utilize nickel titanium SMAs (Flexinol® wire, Dynalloy Inc., diameter 0.012", nominal activating temperature 70°C), formed into 0.048" outer diameter springs, and heat treated at 450°C for 10 minutes to set their shape.

This pilot study investigated the tradeoff between several soft exoskeleton design elements, using SMA spring actuators as the representative actuation structure to produce horizontal adduction on a simulated shoulder joint. Horizontal adduction of the shoulder involves the motion of bringing the arm towards the body midline on the transverse plane. For this pilot study, we employed a simplified benchtop uniaxial "shoulder" model, to evaluate how three different parameters affected the degree of motion afforded by the soft exoskeleton, including: (1) actuator anchor position, (2) actuator orientation, and (3) simulated limb weight. The actuator anchor position is a crucial design element since it causes a change in the length of the shoulder moment arm, and hence the torque produced. A simplest form of system would be to bridge actuators between the torso and arm to maximize the efficiency of actuators along the line of force (Figure 1A). However, from the standpoint of producing a wearable, low form factor system, the bridging of actuators that extend away from the body will potentially hinder the mobility of users. Therefore, we investigate the second variable, actuator orientation, where the actuators are either free to bridge between lever arms (i.e., 'bridged' condition (Figure 1A)) or are constrained in close conformance to the body (i.e., 'conformed' condition (Figure 1B)). Finally, we are also interested in the effect of added weight on the SMA actuator efficiency since it is a closer representation to an actual human arm, and is likely to affect the performance of the actuators.

1.1 Test Setup

A customized test rig was built to simulate a simplified version of the shoulder joint with one degree of freedom (horizontal abduction/adduction). The test rig contains two panels, shown in Figure 2, with panel 1 being the moving panel that simulates an arm, while panel 2 is fixed to simulate a torso anchor. The test rig is made of polylactic acid (PLA) 3D printed parts and a metal base, with woven canvas fabric measuring 4.0 inches by 6.5 inches stretched over the 3D printed rig to simulate the clothing surface on which an exoskeleton might be mounted.

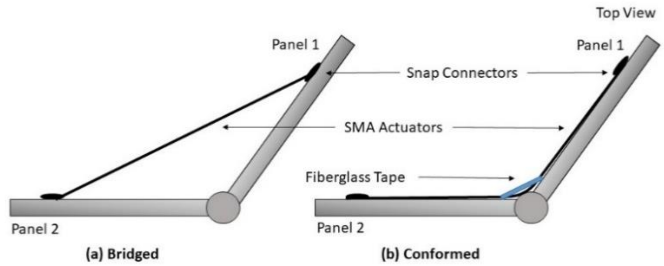

FIGURE 1: SMA ACTUATOR ORIENTATION SCHEMATICS (A) BRIDGED (B) CONFORMED

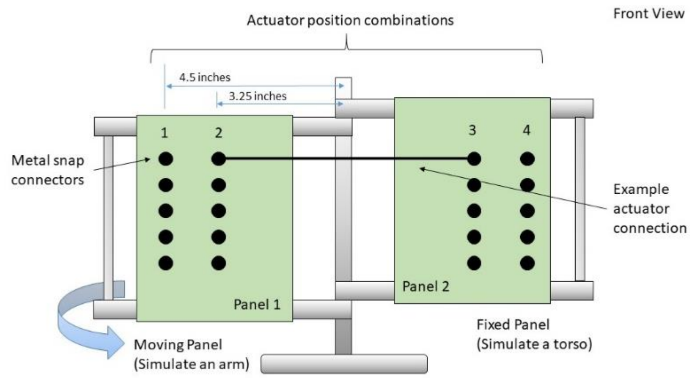

FIGURE 2: 3D PRINTED TEST RIG WITH DIFFERENT ACTUATOR POSITION COMBINATIONS USING METAL SNAP CONNECTORS.

1.1.1 Variable 1: SMA Actuator Anchor Positions

Metal snap connectors are introduced at different locations on the canvas fabric to allow for changing SMA actuator anchoring positions. This provides the ability to easily change the effective length of the moment arm across the joint (Figure 2). Metal snaps at panel 1, column 1, measure 0.75" away from the left edge of the fabric, snaps at column 2 measure 2.0" away from the left edge of the fabric, with panel 2 measurements mirroring that of panel 1. The SMA actuators are snapped on to different positions to complete the soft exoskeleton test rig. The four actuator anchor positions are named based on the column of metal snap connectors the SMA actuators are connected to, and they include position '1-4', position '1-3', position '2-3', and position '2-4' (Figure 3).

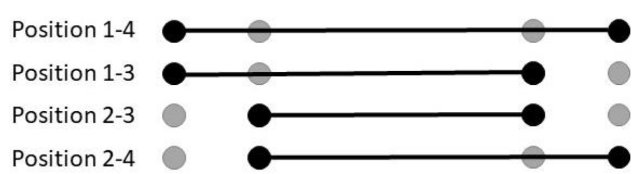

FIGURE 3: SMA ACTUATOR POSITIONS.

Five SMA springs measuring 9.25" when unactuated/stretched (3.0" when actuated/tightly coiled) were used, each evenly spaced 1.0" apart. When unactuated, the SMA springs are deformable, which allows both panels to completely open (180°), simulating complete horizontally outstretched arms (Figure 4A). When an applied current is introduced, the SMA springs contract, pulling the two panels close, up to an internal angle of 30°, simulating horizontal shoulder adduction (Figure 4B).

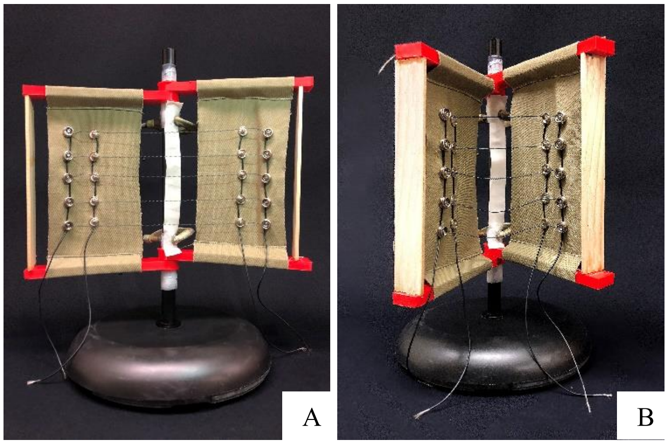

FIGURE 4: (A) UNACTUATED SMA SPRINGS (B) PARTIALLY ACTUATED SMA SPRINGS.

1.1.2 Variable 2: SMA Actuator Orientation

In addition to changing the anchoring position of the SMA spring actuators, we also explored the variable of actuator orientation in relation to the body. As mentioned, the simplest form of a lever would be one that simply allows the SMA actuators to bridge directly across from panel 1 to panel 2 (Figure 1A, Figure 5A), gaping away from the joint. However, due to our interest in wearability, an ideal solution would be one that is low profile and conforms to the body (Figure 1B, Figure 5B). Therefore, we investigated the design tradeoffs between two actuator orientations, 'bridged' and 'conformed'. The 'bridged' orientation only requires connection points as described previously, while the 'conformed' orientation involves the use of a fiberglass tape to restrict the SMA actuators at the hinge joint (Figure 1B, Figure 5B).

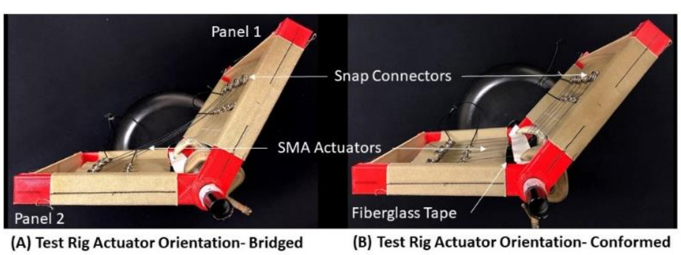

FIGURE 5: SMA ACTUATOR ORIENTATIONS (A) SETUP-BRIDGED (B) SETUP- CONFORMED

1.1.3 Variable 3: Added Weights

The third variable involved added weights on the test rig to evaluate the effect of simulated limb weight on the actuator efficiency. The test rig weighed 4.1 ounces on its own. Two metal weights totaling 1.0 lbs. were clamped to the center of the top and bottom beams of panel 1 (moving panel) and the results were compared to the condition without added weights.

1.2 Test Method

The study was performed with all three variable combinations (one repetition each for this pilot study), with the study test matrix shown in Table 1. In each test condition, the SMA actuators were activated at varying current inputs, ranging from 0A-3A, at 0.5A increments, using a DC power supply (Dr. Meter HY3005F-3). The resulting power inputs for each test condition are presented in Table 2.

TABLE 1: TEST MATRIX WITH ALL VARIABLE COMBINATIONS

SMA Actuator Position	Added Weights-0 lbs		Added Weights- 1lbs	
	SMA Actuator Orientation- Bridged	SMA Actuator Orientation- Conformed	SMA Actuator Orientation- Bridged	SMA Actuator Orientation- Conformed
1-4				
1-3				
2-3				
2-4				

TABLE 2: SOFT EXOSKELETON POWER INPUTS FOR EACH TEST CONDITION

Power Inputs		
Current (A)	Voltage (V)	Power (W)
0	0	0
0.5	0.9	0.45
1	1.8	1.8
1.5	2.8	4.2
2	3.7	7.4
2.5	4.5	11.25
3	5.3	15.9

During each test condition, the system was provided with the specified power and given 15 seconds to actuate. After 15 seconds, the test rig's joint angle (Figure 6) was recorded using a protractor placed directly above the test rig. The power was then shut off, and the actuators allowed to cool before being stretched out to manually reset the rig to 180°. Should the soft exoskeleton arrive at the maximum flexion angle the test rig provides (150°) before the 15 second allotted time, the time it took to fully actuate was recorded.

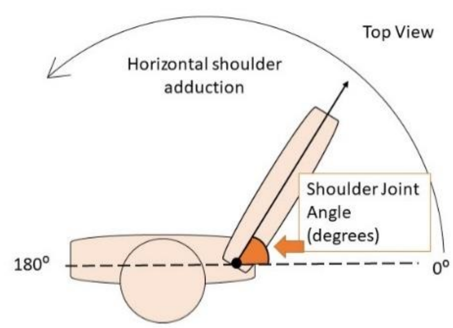

FIGURE 6: SHOULDER JOINT ANGLE MEASURED

1.3 Results

Figures 7 and 8 provide the results for the shoulder flexion angle given all test combinations (actuator anchor positions and orientations), with 0 lbs. and 1.0 lbs. weights added respectively. The results for test conditions below 4.2W were not presented in the graphs since none of the actuators in those test conditions produced any movement in the test rig. The solid bars on the graphs denote the 'bridged' SMA actuator orientations while the shaded bars denote the 'conformed' SMA actuator orientations.

From Figure 7, we see that at 4.2W, only actuator position '1-4 bridged' produced a slight flexion angle (25°). When the power was increased to 7.4W, all actuators produced a reaction, with varying flexion angles. Broadly, we can see that all flexion angles for the 'bridged' conditions (range: 83°-120°) were larger than that of the 'conformed' conditions (range: 40°-83°). Further, there were considerable variations between actuator position test conditions in both 'bridged' and 'conformed' actuator orientations for the specific power input of 7.4W. All power inputs of the following power step-ups of 11.25W and 15.9W produced a complete flexion angle of 150° for the 'bridged' actuator orientation. For the 'conformed' actuator orientation, the flexion angles were lower than that of the 'bridged' actuator orientations, ranging from 90° to 115°.

When 1.0 lbs. weight was added to panel 1 of the test rig, we see from Figure 8 that the actuator performance was markedly reduced. At a power input of 7.4W, only actuator positions '2-3' and '2-4' produced a slight response. When the power was increased to 11.25W and 15.9W, the test conditions where the actuator orientations were 'bridged' produced a complete flexion angle of 150°. On the other hand, the test conditions with actuator orientations 'conformed' saw slightly reduced flexion angles as compared to the test setup without added weights, ranging from 66°-108°.

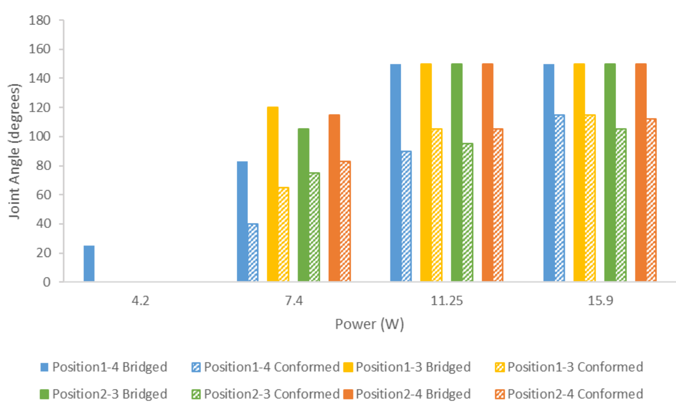

FIGURE 7: SHOULDER ANGLE FOR ALL ACTUATOR POSITIONS AND ORIENTATIONS WITH NO ADDED WEIGHTS

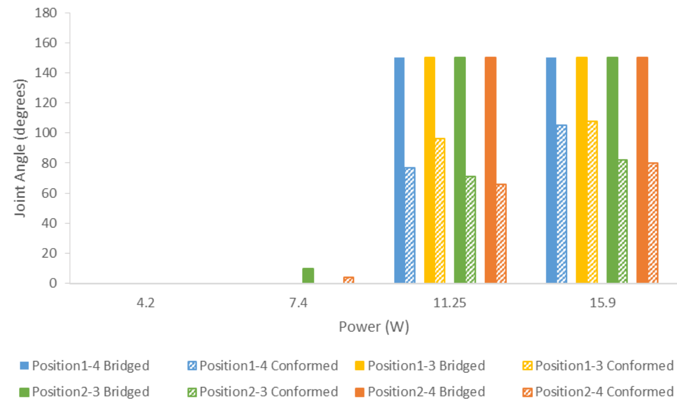

FIGURE 8: SHOULDER FLEXION ANGLE FOR ALL ACTUATOR POSITIONS AND ORIENTATIONS WITH 1.0 LBS ADDED WEIGHT

Since we know that the 'bridged' SMA actuator orientation produced a complete horizontal adduction joint angle of 150°, we were able to extract information in regard to the time it took for the system to fully actuate. From Table 3, we see that when more power was added from 11.25W to 15.9W, there was a difference in the time it took the system to complete its actuation. Further, at a power of 11.25W, for SMA actuator positions '1-4' and '1-3', there was a delay between the weighted and unweighted test setups, but was comparable for SMA actuator positions '2-3' and '2-4'.

TABLE 3: TIME FOR COMPLETE ACTUATION FOR SMA BRIDGED ORIENTATION

SMA Actuator Position	Power (W)	SMA Actuator Orientation- Bridged	
		Added Weights- 0 lbs	**Added Weights-** 1 lbs
		Time to Actuation Completion (seconds)	Time to Actuation Completion (seconds)
1-4	11.25	8	15
	15.9	3	3
1-3	11.25	8	12
	15.9	4	3
2-3	11.25	8	9
	15.9	3	3
2-4	11.25	8	7
	15.9	3	4

1.4 Discussion and Future Work

Revisiting the goal of the project, we were interested in understanding the design tradeoffs of an active soft exoskeleton, between three variables, on the degree of horizontal shoulder adduction: (1) actuator anchor position, (2) actuator orientation, and (3) added weight. Broadly, and as expected, we see a relationship between power input and flexion angle, whereby a higher power produced larger flexion angles (as the SMA actuators are known to produce greater forces at greater powers/temperatures). This is especially evident in Figure 7, where a lower power of 7.4W produced lower, varying flexion angles (range: 40°-120°) as compared to higher power inputs of 11.25W and 15.9W. This is interesting since it points to the fact that given different power inputs, there is potential in controlling the degree of motion the soft exoskeleton may support. Future work will involve more power input step-ups to map specific power inputs to flexion angles for more fine-tuned control.

In terms of actuator anchor position, when the joint angle was not at its maximum of 150°, we observe variations between actuator anchor positions. This tells us that the actuator anchor positions do indeed play a role in the functionality of the system due to the differences in flexion angles and is likely influenced by the changes in length of moment arm and the resulting torque. However, a limitation to the current setup is that the different degrees of pre-stretch tension when the SMAs are in their unactuated state were not accounted for. Since the SMAs are all measured to be 3.0" tightly actuated/coiled, when stretched to different actuator positions, the degree of tension of the SMA actuators in each condition might be slightly different. For example, when the SMA actuators are affixed to positions '1-4', they have a wider separation distance than when they are affixed to positions '2-3', which could give rise to varying pre-stretch tension in the SMAs, hence affecting their performance. Since the SMA springs are the most effective when stretched to their maximum length when unactuated, actuator fixture points with a smaller separation distance might cause the SMA actuators to underperform if they are not similarly reduced in length. Future work will dive deeper into understanding the influences the actuator anchor positions and pre-stretch tensions provide and strategies we can employ to select an anchor position and tension that will serve the needs of the users in having a system that is functional, efficient, and wearable.

The results in terms of actuator orientation painted a much clearer picture. The 'bridged' test conditions across all actuator anchor positions provided a larger flexion angle compared to the 'conformed' test condition. This comes as no surprise since the angle between the force vector and the lever arm vector is reduced in the 'conformed' test condition. However, from the perspective of wearability, the 'conformed' test condition is likely to be much more comfortable for the user since the soft exoskeleton will be close to the body (i.e., low form factor), with no externally-extending actuators that might inhibit mobility, as well as the potential reduced effects on a user's body schema (i.e., it allows for discreetness of the system). Future work will investigate this further to better understand the design tradeoffs between the different actuator orientations to maintain both functionality of the system as well as developing one that the users will enjoy.

In terms of added weights, unsurprisingly, we see differences in flexion angle given a specific power input. When more weight was added, more power was required to achieve a specific flexion angle. This suggests that SMA-based shoulder exoskeleton systems should consider supplementary actuation schemes (e.g., pneumatic bladder systems) to specifically offload the weight of the arm prior to horizontal adduction using the SMA actuator system. The idea is to use (1) soft pneumatic systems that use inflation to apply force to support vertical shoulder adduction (i.e., providing lift from the inferior aspect by pushing the arm upward from below) and (2) SMA actuators to apply force to support horizontal shoulder adduction (as in this study). Therefore, the weight of the arm will be mostly offloaded, achieving close to a 'zero weight' condition for the SMA actuators to function optimally and efficiently.

Another interesting insight that we gathered from this study is the time it took for complete SMA actuation in the 'bridged' orientation: with lower power input of 11.25W, the actuators fully activated at 8 seconds for the no weight conditions for all actuator positions and between 7-15 seconds for the added 1lbs weights conditions. All conditions regardless of actuator position and weight, actuated completely within 3-4 seconds for the higher power input of 15.9W. While an argument can be made that from an engineering standpoint, the faster the soft exoskeleton completes its actuation, the better it is; the fact is that when placed on a person, such a quick response time may prove to be undesirable if it startles the user. In this case, a slower actuation rate may be more acceptable by users. These response times that were captured in the results are also too slow for real-time, high frequency scenarios, and as a larger goal of the project, we are considering this application for more quasi-static response scenarios that are slower. An example would be one that supports adduction of the arm to a central location so children are able to access their mouths for eating or exploring. Future studies should include both, more fine-grained power input step-ups to better characterize the actuator response, as well as gathering user input for a more comfortable experience design.

One limitation of this study is the simplified nature of the test rig. We attempted to simplify the current model to only produce horizontal adduction using a uniaxial model. Clearly, the shoulder joint is a much more complex system and future work will involve producing a test rig that can more closely simulate a shoulder joint to better understand the influencing variables in the design of a successful soft exoskeleton system. In parallel with that, work will also be done to design the system for actual use scenarios in an exoskeleton form factor. Since the SMAs used in this current system activate via joule heating at approximately 70°C, having them directly on the skin will induce burns. Work is currently being done to investigate different insulation materials as well as SMAs with different alloy compositions to lower targeted activating temperatures for better excess heat management.

CONCLUSION

In conclusion, this project takes a first step into understanding the various design variables when developing a wearable soft exoskeleton through a benchtop pilot study. The system uses a non-traditional soft robotic actuation mechanism—SMA coil actuators to produce the necessary forces for horizontal shoulder adduction. The major takeaway from this study is the understanding of the tradeoffs between functionality and usability: as expected, we see a decrement in functionality when we attempt to increase usability by changing the actuator orientation from a 'bridged' to 'conformed' scenario. We also see changes in performance as measured by ultimate flexion angles when actuator positions are modified and when weights are added. The understanding gathered about force/torque generation with an SMA mechanical actuation system has wider implications on other soft robotic applications such as the design of exoskeletons, braces, and compression garments. Future work will dive deeper into understanding the design tradeoffs these variables provide in order to create a wearable, soft exoskeleton system that is capable of effectively supporting or manipulating movement of the body while maintaining the benefits of comfort and discreetness of a regular garment.

ACKNOWLEDGEMENTS

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