DEVELOPMENT OF ERGONOMICALLY DESIGNED FUNCTIONAL BRA FOR WOMEN WITH HEMIPLEGIA

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1. Introduction

Hemiplegia is complete paralysis on one entire vertical half of the body, which is a common effect of brain stroke [1] Brain stroke is counted as the third most common cause of reduced disability-adjusted life years [2]. Previous studies reveal that only in France a stroke occurs every 4 min, that is, around 130,000 per year [3]. Although the pieces of evidence indicated that the gender differences in stroke risk factors are marginal, however, its impact is stronger in women since women account for more than 60% of total stroke deaths [4, 5].

Brain stroke is recognized as a leading cause of disabilities and life-long immobility, for example, hemiplegia. The most common challenge for women with hemiplegia is to carry out their daily living activities comfortably due to the problem of joint pain and decreased mobility. Swelling, stiffness, and tenderness in joints are some of the side effects that inhibit mobility. This is the major cause of pain and also restricts the mobility of moving fingers or hold anything with them. Also, it limits the movement and bending of weight-bearing joints. The immobility, as well as the painful movement of joints, affects the clothing needs of women with hemiplegia [6]. For example, backward stretching of arms is a normal action for women in fixing/fastening a bra. This usual action has severe implications in women with hemiplegia. One of the major functions of a bra is to keep breasts in good shape. It reduces breast ptosis (sag) by lifting the breast. Women look more attractive by wearing a bra underneath clothes [7]. Bra-related literature has typically centered on younger women and rarely considers the role of the bra among older women and no literature was found on bra preferences by the women with hemiplegia. The impact of hemiplegia on a woman’s body concerning intimate apparel especially bra preferences remains poorly understood.

When designing any product, the first thing that needs to identify is consumer’s behavior. For clothing, it is really important that his/her physical, physiological, and morphological needs should be studied before designing, as it is in direct contact with skin and cause discomfort.

Women with hemiplegia are spending most of their time in a wheelchair or lying prolonged time in bed, that is why thermal comfort properties are more important [8]. Transmission of moisture (sweating) from the skin is also a frequent problem for such females. Therefore, the garments to be used for direct contact with the body must have special functional properties and should be manufactured with the fabrics that exhibit special properties, such as:

1. Tactile properties – particularly when it designed for skin sensitive folk;

2. Thermal comfort – another feature turns out to be very important for hemiplegic females who spend most of their time in bed;

Abstract:

Hemiplegia is the lifelong paralysis, caused by brain stroke that affects one side of the body. Stroke exerts a great threat to patient’s health and lives, and hemiplegia after stroke may severely affect their activities of daily life including self-dressing that causes fatigue and frustration and ultimately ended with “dependence on others.” This situation damages the sense of dignity, especially for women, while independently dressing intimate apparel like bra. The research through the design approach is used as the conceptual framework to design and evaluate bra for the women with hemiplegia. Three design criteria were identified from which specifications were developed, and their interrelationships explored through an interaction matrix. This article presents a research work on improving bra design, adjusted to the special needs and demands of an individual with hemiplegia, by using bi-layer knitted fabric, magnetic fasteners, and shape-memory alloys. The findings of the current study showed that adaptive bra design offers independence, concealment of the disability, and comfort and psychological contentment. This adaptive bra promotes the harmony between functionality and esthetics.

Keywords:

Ergonomics, apparel technology, magnetic fasteners, shape-memory wires, bi-layer knitted fabric, hemiplegia
3. Dehumidify perspiration – can dehumidify moistness produced by perspiration (the most widespread problem) and can maintain optimal humidity and air circulation [9];

The weak muscles and limited and complicated motor movement of the hemiplegic women influence the dressing capability and handling of fasteners [8]. Fasteners are the essential part of a fastening system used to hold together at least two pieces of material. For the bra, the traditional way of fastening is to use hook and eye or multiple hooks and eyes. However, in case of special needs, one has to find alternative means of fastening that is easy to handle with limited mobility. Sometimes, however, there are real needs for alternative means of fastening to satisfy special considerations involved with regard to a particular clothing item. One specific example would be the conventional bra, wherein the traditional fastening means involves a hook and eye configuration or multiple hooks and eyes. Most women feel more comfortable dressing themselves, even though it may take them longer to do so. Simplifying clothing fasteners in a variety of ways can compensate for the loss of their motor skills. Velcro closures made a good substitute for hook and eye configuration [10]. Nevertheless, velcro fasteners were not much compatible with weak and fragile hemiplegic females with almost numbly hands to handle fastening.

The main goal of the current research is to facilitate the self-dressing of bra for women with hemiplegia. As the bra is a body-shaping garment so it is supposed to be body-fitted. It is very difficult for hemiplegic females to put on independently such body-fitted garments. During the research work, attempts have been made to ascertain the biomechanical problems faced by women with hemiplegia while dressing and undressing of bra and defined functional requirements. Based on the biomechanical limitations of hemiplegic women, prototype designs of the bra were developed by combining the knowledge of human engineering (ergonomics), textile materials, and apparel technology. Special modifications were made in the bra design to de-emphasize visual evidence of a stroke-affected women’s disability and strengthen function and convenience to meet the needs of body activities. Bi-layer knitted fabric was proposed to get optimum moisture management properties of the fabric. Magnetic fasteners can facilitate weak and lethargic females with limited movement and almost numbly hands to control fastening. Bra designs with a transformable back panel with the integration of shape memory alloys can benefit those who have trouble dressing by allowing the bra to wrap around and fit the wearer without external help.

2. Experimental

2.1. Materials

Flexible magnetic fasteners were purchased from SYSTEMMAG®, France. Shape-memory Nitinol wires were brought from Kellogg’s Research Labs, USA. Bi-layer knitted fabric in rib structure was developed at Combined Fabrics Limited, Pakistan.

2.2. Methods

This research builds on the knowledge from therapy, human engineering (ergonomics), textile materials, and apparel technology. Given the complexity and multitude of challenges, and to balance the various requirements of function, technology and esthetic, we adopt a research-through-design approach to generalize applicable and communicable knowledge through the development of prototypes, as shown in Figure 1.

The approach of research-through-design comprises methods and processes from design practice, which has been used as a common methodology in human–computer interaction studies [11].

The process of research through design is based on the following basic principles:

1. Mandatory consideration of user needs;
2. Identification of requirements and needs of hemiplegic women regarding bra;
3. Selection of modern materials and technologies that can be used in the design concept;
4. Identification of the main factors that are of decisive importance in the development of the concept of adaptive bra design;
5. Evaluation of the concept is a key step in the determination of the effectiveness of decisions taken in conceptual design.

The aforementioned information indicates the importance of providing a scientifically based approach to the selection of the components of the package of materials in the design of an adaptive bra.

Figure 1. Schematic illustration of the research-through-design process.
2.2.1. Empathy and define requirements

The work has been done in collaboration with Haute-Alsace regional hospital. A questionnaire was formulated for this survey study. Hemiplegic females and occupational therapists were interviewed, and their concerns and apprehension about traditional bras were recorded. Three occupational therapists age ranging from 30 to 40 years and 10 women with left hemiplegia aging between 35 and 45 years were selected and interviewed. Participants’ observations and apprehensions about intimate apparel, especially about the bra, are presented in Figure 2 (white dots indicate the comments of patients and blue dots indicate the comments of occupational therapists). Permission was obtained from them to publish this data.

As most of the bras are fasten up at the back therefore participants expressed anxiety about comfort while wearing the bra as well problematic maneuvers to don it.

Further, patients who are clumsy and poor in fine motor skills had always felt difficulty in manipulating fasteners, that is, hucks and eyes, buttons, and zippers. Most of the time, the benefits of wearing the bra are outweighed simply due to the hard work required for wearing bras for many women. Resultantly, most of the aged women are become reluctant or stop wearing a bra completely and started wearing a shelf bra camisole or undershirt; none of these provided the necessary breast support. So, all this hard work required in wearing a brassiere and inadequate body movement, problematic fasteners and discomfort make it an awkward garment and most of the elderly avoid wearing a brassiere.

2.2.2. Potential solutions

A number of different needs and restrictions govern the choice of material intend to use for adaptive bra for women with hemiplegia. It should be comfortable and appropriate for any physical requirements. In addition, it should be easily available for reasonable price. The wear comfort of adaptive bra can be achieved by thermo-physiological, skin sensorial, ergonomic, wear, and psychological comfort. By keeping in view, the requirements and constraints of hemiplegic females following solutions were proposed, as shown in Figure 3.

Knitting is one of the widely used techniques to make fabrics. The demand of knitted fabrics is increasing due to its comfort. In addition, its simpler production process and low cost make it attractive to be used in different types of products. Stretchability and comfort of knitted fabrics are some other features that increase its usage in clothing. The structure of knit fabrics also exhibits better absorption properties and can transmit perspiration from the body [12-14]. Therefore, bi-layer knitted fabric was proposed to get better comfort properties of the fabric. It was suggested to manufacture bi-layer knitted fabric in such a way that the outer layer is made of cotton and the inner layer, which will be in contact with the skin, is of polyester yarn to improve the wicking ability of fabric by improving capillary action. To get optimum fabric comfort, it was proposed to apply hydrophilic finish on the fabric.

Adapted magnetic fasteners were proposed to integrate, which can facilitate weak and clumsy hemiplegic having a limitation in movement and almost numbly hands to manage fastening. Magnetic fasteners could be advantageous because they are easy to use and provide adequate fastening. Due to the use of strong flexible magnets, the fastener parts will be automatically self-aligned into the magnetically coupled configuration once the fastener parts are in magnetic proximity to each other. On the other hand, the magnetic fastener parts could be easily detached by relative tilting to move the fastener parts away from the magnetic coupling. In particular, magnetic fasteners are particularly useful in situations where fasteners are required to be done and undone by a single hand and in a short time.

The people with disabilities have additional apparel-related challenges due to their specific requirements and preferences. During the study, the interviewees mainly showed their concerns about the back-closure bras because the putting on (donning) and putting off (doffing) a back closure bra required a series of body movements. The main challenges impacting the patients during donning and doffing of back closure bra were: (i) inserting their arms into the straps, (ii) approaching backwardly for fastening the hook and eye closure, and (iii) accurate adjustment of the shoulders straps and breasts inside the bra cups. A solution to these problems could be the use of front-fastened bra but unfortunately, availability of front-fastening bra closures is very limited. Moreover, this front fastened bra unable to provide enough support to breasts and sometimes hemiplegic women need help to pull it around to the

Figure 2. Participants’ comments about the bra.
other shoulder, they may get it on, but then the strap gets lost behind and they can’t reach it, as shown in Figure 4.

Furthermore, this bra design is supposed to fit superbly due to its fixed adjustment, contrary to the back-closure bra, which is fitted with multiple rows of eyes.

To overcome this problem, the idea was to use some smart material, which has kinetic effect. The word “kinetic” refers to garments that can be even further reconfigured, whose shape could more fundamentally be altered through the use of heat. Materials that move introduces a particular category of smart materials able to react to a stimulus acting with a kinetic effect. The general characteristic of these materials is their ability to move. As the movement, that characterizes those produces a change of physical form, we could also name them materials that change shape or kinetic materials. Their shape changes can be free and casual yet also programmed and controlled. Shape memory alloys can attain shape by using the body as a source of energy. It can acquire different shapes with subtle movements that cannot be achieved otherwise. Besides, there is no noise and can function relentlessly. The use of SMA will help in the widening of the back panels while wearing and it tends to come back to its programmed size and shape after wearing with body temperature.

2.2.3. Development of prototypes

The disparity between the capacity of a body and the mobility required to put on and fasten a bra could be mediated by creating an ergonomic design. We set out to create an adaptive bra design to identify the main technical and design challenges and to seek design opportunities. Three designs were (A, B and C) were proposed as shown in Figures 5–7. Design A as shown in Figure 5, magnetic fasteners were used at center front and on extended bra strap at the left side, the purpose of using magnetic fasteners was to facilitate weak and clumsy hemiplegic women having a limitation in movement and almost numbly hands to control fastening with a single hand.

The purpose of using an extended bra strap was to provide more grip areas to fasten the front fastened bra with a single hand. One-handed removal of the bra in the front position has further facilitated by the addition of a finger/thumb loop. The purpose of the finger/thumb loop was to swing the bra fastener to the front position and further utilize the loop to unfasten the bra with a single finger or thumb, while the fastener has positioned in front of the wearer. As discussed earlier, the women with hemiplegia faces difficulty while wearing front fastened bra independently because they require assistance while pulling front fastened bra around to the other shoulder; they might be managed to get it on, but during this progression, the strap could be get lost behind the body and most likely get out of their reach. To overcome this problem, plastic stays made of flexible plastic material were inserted at center-back as shown in Figure 5. In this Design B, as shown in Figure 6, magnetic fasteners were used at center front and on extended bra strap. The shape of an extended bra strap is different from the previous design; in
this design center-front, magnetic fasteners are attached with the extended bra strap.

Second, to facilitate the recognition of magnetic fasteners inserted in an extended bra strap highlighted that area with bright yellow color. To avoid the twisting of the back panel while wearing more flexible plastic stays were added as compared with the previous design, as shown in Figure 6. To avoid the slippage of shoulder straps, silicon adhesive material was added under the shoulder level of shoulder straps.

But the addition of plastic stays provided solution against twisting, but it reduced the elasticity of the back panel. So in Design C, as shown in Figure 7, shape-memory wires were used, which would facilitate due to its shape-retaining property. Transferable back panel can avoid twisting of the back panel as well as it could provide further facilitation in wearing due to its extension and contraction property. In Design C, the placement of flexible magnetic fastener and shape of an extended bra strap is the same as in Design B, as shown in Figure 7.

2.2.4. Evaluation of prototypes

Based on the principles of a conceptual design of the adaptive bra stated earlier, a scheme has been developed for the evaluation, as shown in Figure 8.

The adaptive bra evaluation, first of all, is realized by defining the design situation, the main and additional functions of the bra. Proceeding from this, it is important to choose and justify the materials because this information is the basis for the substantiation of combining the elements of a bra (materials and means of influence).

2.2.4.1. Fabric evaluation

Evaluation of fabrics for its performance is mandatory particularly during the design and development of adaptive intimate apparel. By investigating the properties of fabric through textile testing, it is possible to determine its suitability for its intended application. The physical properties of textile materials, which contribute to physiological comfort, involve a complex combination of heat and mass transfer. The comfort of the fabric is attained through the transmission of sensible and insensible perspiration. Intimate apparel fabrics chosen should have quick drying and good wicking property to handle excess sweat produced by the body. Drying and wicking ability of intimate apparel fabrics are key functions related to comfort. These properties are important to handle perspiration produced by the body. Wicking is the form of capillary action where liquid can move from one part to other even in a condition where gravitational forces are not available. Smaller the size of capillary tubes more will be a capillary force and that will increase the wick ability of the fabric. Water vapor permeability and thermal resistance are measured by using moisture management tester according to the ISO 11092 standard.
Furthermore, another important factor for evaluation of fabric comfort intend to use for adaptive intimate apparel is air permeability. The air resistance values of the multilayer knitted fabrics were measured individually by using the Kawabata evaluation system under automatic air permeability tester.

2.2.4.2. Magnetic fasten-ability evaluation

To evaluate the fasten-ability of magnetic fasteners evaluation, tensile strength tester was used. The test was conducted at one-fourth part of bra, as shown in Figure 9, at the velocity rate of 100 mm/s.

2.2.4.3. Evaluation of NiTi wires

The memory configuration of the alloy must be first set in the material by holding it in the desired shape while annealing it at 450°F to 500°F for 60 min. Once a certain shape is set, the alloy can then be deformed at temperatures below its transition temperature range (TTR). On heating through the TTR, the original shape of the alloy is restored. A review of the literature indicated that the application of the shape-memory phenomenon of nickel-titanium alloys is possible to use in apparel [15]. The shape memory property has been quantified in some aspects. The purpose of the below investigations was to quantitatively analyze the deformation force required to deform the memorized shape as well as the shape-memory phenomenon of wires made of nickel-titanium alloys.

2.2.4.4. Deformation force energy evaluation

The samples of NiTi wires were analyzed for deformation force to evaluate the compatibility of these wires with body movements. Three types of wires were used, and parameters of wires are given in Table 1.

![Table 1. NiTi wire parameters](http://www.autexrj.com/)

| Sr. No. | Diameter (mm) | Transition temperature (°C) |
|---------|---------------|-----------------------------|
| 1       | 0.5           | 20                          |
| 2       | 0.5           | 35                          |
| 3       | 0.25          | 35                          |

The tensile test was carried out being based on ISO 2062:1993 standards, using tensile strength tester, as shown in Figure 10.

2.2.4.4.1. Shape recovery percentage evaluation concerning time

To evaluate the temperature at which shape memory wires recovered its programmed shape, a test has been performed in Instron thermal chamber, as shown in Figure 11. The length of the programmed NiTi wire was 30 cm; it was deformed up to 30% of its length which was 39 cm. A scale was fixed inside the chamber to calculate shape recovery percentage of Nitinol wire and time was recorded to see how long it would take to come back to its programmed shape.

2.2.4.4.2. Survey

To evaluate the design, we had wear trial test followed by recording feedback in the form of the survey form. Three occupational therapists and 10 women suffering from left hemiplegia aging between 35 and 45 years were selected and interviewed during this study and record their feedback by filling the questionnaire. Permission was obtained from them to publish this data.

3. Results and discussion

The qualitative and quantitative assessments were made to validate the functionality of the adaptive bra. Materials were tested to validate their suitability for end-use. For the qualitative evaluation of prototypes, a wear trial test was conducted, and a feedback was recorded in the form of answers to the questionnaire.

3.1. Air permeability and thermal resistance of fabric

By applying hydrophilic finish on double knit rib fabric the water vapor permeability increase significantly (paired T-test applied), air permeability and thermal resistance reduced slightly as shown in Figure 12, but the feel of fabric become so soft, which are highly beneficial to the overall comfort of fabric, intend to use for the adaptive bra.

3.2. Fasten-ability of magnetic fasteners

The stroke-effected women patients having hemiplegia affliction are generally weak and clumsy with limited physical activity [16, 17]. An increase in their circumference is up to 6 cm as a result of breathing [18]. Figure 13 is drawn for the mean value of all 10 samples for both designs.
3.3. Evaluation of NiTi wires

Wires of nickel-titanium alloys are known primarily for their two unique properties of superelasticity and the shape-memory phenomenon. This investigation was undertaken to quantitatively analyze the deformation force energy and shape-memory phenomenon of wires made of nickel-titanium alloys.

3.3.1. Deformation force energy evaluation

The prototype bra was developed in plus size, and the purpose of inserting Nitinol wires was to get it back to the required size, so we need a certain amount of force to keep it at the required size after wearing. During any physical activity, certain elongation required to provide the ease of movement to busts but to provide proper support, the bra should exert certain pressure to hold the busts to avoid excessive movement [19].

As the graph in Figure 14 indicates that at 100 mm elongation, the force exerted is 1 Newton in case of Nitinol wire of 0.5 mm diameter and transition temperature of 20°C which is quite compatible to hold the bra properly, and this force will not give pressure to the body which can cause pressure marks.

NiTi wire with a diameter of 0.5 mm, the transition temperature of 20°C has more tendency to stay at its programmed shape when in contact with the human body due to its lower transition temperature as compared to NiTi wire with a transition temperature of 35°C.

3.3.2. Shape recovery percentage evaluation concerning time

The comparison of both designs showed that the fasteners stayed fastened up to 5.5 cm (55 mm) for Design 1, and for Design 2, it stayed fastened till 4.5 cm (45 mm) elongation. However, in case of Designs 1 and 2, it can stay fastened even at the extension of 20 and 18 cm, respectively. Therefore, Design 1 is the preferred design, and we can use these magnetic fasteners even in our regular bra.

The shape memory wires should recover its shape at body temperature so that any extra energy source could be avoided. Nitinol wires tend to recover its shape in 2 min at 30°C, as shown in Figure 15.
4. Conclusion

- The polyester cotton bi-layer knitted fabric with rib structure has selected based on moisture management comfort properties. The use of hydrophilic finish on fabric made it a more suitable choice for next to skin application owing to good one-way liquid transport, high absorption rate, spreading speed, and its ability to keep skin dry.

3.4. Survey

The results of the specific study are presented in Figure 16. During the survey, the functional features of the newly developed bra were evaluated.

Survey results revealed that Design “C” was the most preferred design due to its comfort and functionality and is presented in Figure 16. The main features of its preference were:

1. The added new feature, the front extended loop make available large grip area that enables the hemiplegic females to fasten bra single-handedly.

2. The use of shape memory wires in the back panel facilitates donning and doffing as the back panel was designed in a bigger size and due to the use of shape memory wires, it will contract and come to the required size owing to body heat.

We have taken 30°C temperature as it is close to the human body temperature, which is 35°C. The reason behind taking less temperature than the body temperature was, there will be an impact of environmental temperature on the garment as well so better to keep it a little low so that it can relate with actual conditions.
- The use of flexible magnetic fasteners facilitates hemiplegic females with reduced strength, mobility and sensitivity in their hands to manage fastening of a bra. Owing to their magnetic capability, the fasteners can pull themselves together at once, vastly reducing the fatigue and time required to fasten bra.

- Nickel-titanium alloys (NiTi-NOLs) are responsive smart materials, which change their shape and superelasticity within the range of human body temperature. Bra designs with the transformable back panel will benefit those who have trouble dressing by allowing the bra to wrap around and fit the wearer without outside help due to its extension and contraction property at human body temperature.

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