Development of adaptive bust for female soft body armour using three dimensional (3D) warp interlock fabrics: Three dimensional (3D) design process

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Abstract. The traditional two dimensional (2D) pattern making method for developing female body armour has a negative effect on the ballistic protective performance as well as the comfort of the wearer. This is due to, unlike the male body armour, the female body armour manufacturing involves different darts to accommodate the natural curvature of the female body, i.e. bust area, which will reveals the weak parts at the seam and stitch area while ballistic impact. Moreover, the proper bra size also plays an important role not only in bra design but also in the design of a women’s ballistic vest. The present research study tried to propose the novel 3D designing approach for developing different volumes of breast using feature points (both bust surface and outline points) in the specific 3D adaptive mannequin. Later the flattened 3D bra patterns of this method has been also compare with the 2D standard pattern making in order to modify and match with 2D traditional method. The result indicated that the proposed method which conceives the 3D patterns on the 3D bust is easier to implement and can generate patterns with satisfactory fit and comfort as compared to 2D patterns.

Keywords: 3D virtual mannequin, 2D and 3D bra pattern, women soft body armour, Adaptive bust.

1. Introduction
In today’s scenario many law enforcement agencies have made it mandatory for their officers to wear ballistic vests while on duty. Meanwhile in order to be worn by the officer, the vest generally should be designed in such a way that it has to be properly fitted with proper material which has a better resistance to projectile penetration, reasonably light in weight and flexible. Different data also shows the number of women joining law enforcement work has been steadily increasing across the world. For example, in the United States according to Bureau of Justice Statistics (1993) in 1970 among all the members only 2% were women but the number has been increased to 7.6% in 1987, 9% in 1991, 12% in 2007 and 2011 and 15% in 2015[1]. However, most pieces of body armour are designed to be worn by men otherwise traditionally designed women armour which can often result uncomfortable and ill-fitting when worn by a female body. Moreover, unlike male body armour, design and manufacturing of female body armour encounter problems due to the curvy body shape of females. In order to accommodate the bust area different methods such as traditional cut-and-sew with dart, stretch folding
and fabric folding have been used so far. Developing the female body armour using those methods faces ballistic performance, well-being and comfort problems due to various reasons as well [2]. However, in order to ensure the better fitness to the wearer, especially for female, the trend is now to fulfil an order where all measurements are known which basically determine the size of the vest.

The bra size plays an important role in the design of a woman's ballistic vest. But the current system of developing bra size is mostly inaccurate which causes uncomfortable and less fitting garment. This is due to availability of many different styles of bras, lack of standardization within the brands and more a matter of guesswork, trial, and error than precise measurements. Usually brassieres sizes vary depending on the system of standards set in various countries and vary from one manufacturer to another. These standard sizing systems are typically used to label off-the-shelf bras and are not used for made to measure. The shape, size, symmetry, and spacing of women's breasts vary considerably, affecting the bra and cup size. Even taking into account the relationships between the heights and girths of human body, the shape and size of woman breast can varied significantly with no correlations to the others measurements[3]. Obtaining the correct size is further complicated by the fact that the size and shape of a woman's breasts fluctuate with weight gain or loss. The development of adaptive models morphotypes or virtual custom models is a challenge worldwide industrial, essential accompaniment to the field “ready to wear” and mass customization are crucial to direct garment design in 3D [4][5]. In order to overcome those problems, different researchers came up with different proposals and solutions. One of our previous study has proved the efficiency of 3D shape of body armour using specific rotating darts technic with 2D fabrics [5]. Angle interlock structures have been also found as a good material for the development of female body armour due to its specific characteristics like good elastic behaviour properties and good mould ability capacity due to its low shear rigidity as compared to other woven fabric structures [6] [7] [8].

2. Experimental methodology
Basically a more fitted bra will be achieved only by purchasing a custom-made bra, which considers different parameters like the position of a woman's breasts on the chest, its asymmetrical positioning and size of the breasts. This particular study first tried to explains the process of conceiving and realizing adaptive bust for different volumes of breast on a 3D mannequin of a woman which will be very important in the developments of female body armour. An attempt has been also made to realize cup sizes for 90B size on the mannequin and conceiving the basic corset patterns directly on the mannequin. Later the study deals on the 2D-3D reality to compare the proposed corset pattern on 3D with the traditional 2D pattern made from standard measurement of the same size. These corrected patterns are then adapted to change the volume of the breast in the adaptive bust.

3. The 3D design process of adaptive bust
The first step to start the process were conceiving a particular morphology of woman mannequin which was issued from the 3D scanning process and later transferred to the special CAD software called Design Concept 3D (Figure 1). At the beginning of the process two different co-ordinates as shown Figure 2, one at the centre of the mannequin on the bust level and another at the centre position of the mannequin bust have been placed. The later point shall fall on the surface of the bust by which it was derived by projecting the centre front point on the Z+ axis.

Figure 1: 3D mannequin of a woman
Figure 2: Co-ordinate position
Figure 3: 3D mannequin bust outline
Using the different tests of various parameters, an optimum values has been obtained to form the natural plane of origin of the bust. Later as shown in Figure 3 using this plane and 3D mannequin the curve of intersection have been defined. However, in order to manage the volumes of the breast and conceive an adaptive bust, different reference point shall established on the surface of the bust. To achieve this coordinate at the origin of bust point has been duplicated in both X and Y axis by rotating with different angles (75, 50, 25 and 90 degree) which finally give different new planes of coordinates as shown in Figures 4 and 5.

![Figure 4: Different planes of coordinates in x-axis](image1)

![Figure 5: Different planes of coordinates in y-axis](image2)

The intersection curve between those new coordinate planes and the bust surface were identified as shown in the Figures 6 and 7. The required feature points have been located on the intersection of the horizontal and vertical profile while making mesh on the bust surface. Generally two kinds of points have been developed as indicated in Figure 8. One the outline point which lays on the outline surface of the bust to determine the size and another point on the surface of bust with the intersection of vertical and horizontal profiles for governing the breast volume.

![Figure 6: Vertical profile](image3)

![Figure 7: Horizontal profile](image4)

![Figure 8: Mesh on the bust surface](image5)

Figures 9 and 10 shows the different individual line drawn from the central point of the bust to the outline and surface reference points. This line will be considered as a guideline for the direction of the reference points from the origin of the bust. In addition, the curve which corresponds to the various corset sizes also created on the line of centre front plane indicated on Figure 11 and after translated on to the plane of origin of bust (shown in Figure 12).

![Fig. 9 2D outline points](image6)

![Fig. 10 3D surface points](image7)

![Fig. 11 Corset sizes curve](image8)

![Fig.12 Translated corset sizes](image9)

As you can see from Figure 13, in reference to the translated curve for various corset sizes it was clearly shown that the conceived 3D mannequin laid on the size 90B.
Moreover, the 3D design of bra starts with by determining some reference points which is directly marked on the 3D mannequin bust. The 2D patterns are used to define the cleavage, style line and dart points which is necessary to conceive a bra. These parameterized points and their corresponding profile allows to manage the volume of the chest for a given morphology of the woman breast. Concerning the bra design in virtual reality, the most important marked point allowing the precise location of bra on the mannequin body defines the beginning of bra cup profile which was validated in the 2D pattern. Later considering the curves drawn to connect the above marked points to the centre of the chest separately, the curves are created by linking the correct points. The set of four different curves makes a region shown in Figure 14. In order to assume the 2D shape of the bra, it was necessary to create the different regions based on these curves seen as the contours of appropriate elements of bra shape. The mesh (Figure 15) has been built on the surface of the mannequin regions and then easily flattened into 2D to compare with traditional 2D patterns.

4. Result and discussion

4.1. Developing different volumes of Adaptive bust on a 3D mannequin

After getting the good value of bra, we now tried to determine different volumes of breast with reference 90B size mannequin by projecting both the bust surface point and outline points. This will creates the new corresponding point using the prolonged function and value of the parameter. Defining and naming the different prolonged points makes it easier to determine a reference to the point and realizing corsets of varying volume.

| Description            | Curve Name | Point references | 1  | 2  | 3  | 4  | 5  | 6  | 7  |
|------------------------|------------|------------------|----|----|----|----|----|----|----|
| 1st Horizontal Curve   | HC1        |                  | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 2nd Horizontal Curve   | HC2        |                  | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 3rd Horizontal Curve   | HC3        |                  | 8  | 10 | 10 | 10 | 10 | 15 | 8  |
| 4th Horizontal Curve   | HC4        |                  | 3.75 | 6.72 | 8.30 | 10.2 | 12 | 15 | 8  |
| 5th Horizontal Curve   | HC5        |                  | 8  | 10 | 10 | 10 | 10 | 15 | 8  |
| 6th Horizontal Curve   | HC6        |                  | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 7th Horizontal Curve   | HC7        |                  | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Out Line points        | LC (all equal) |          | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |

For example, Table 1 has shown the parameters to determine the 95B size with the value of 5.5mm for all outline bust point and approximately 10mm for the different surface bust points. The result of the above parameter can be seen in Figures 16 and 17.
However if you see the conceived adaptive bust based on the different prolonged point with the given parametric value, some part of the surface in uneven which needs to be corrected.

Table 2. Adjusted prolonged point value for adaptive 95B size bust

| Description               | Curve Name | Point reference | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---------------------------|------------|-----------------|---|---|---|---|---|---|---|
| 4th Horizontal curve      | HC4        |                 | 8 | 8 | 8 | 10| 12| 15| 8 |

As shown in Table 2 and Figure 18, by changing the parameter on that particular area, HC4, it is also possible to achieve a smooth and even surface. Normally the involvement of number of reference point to realize the better and smooth surface of the adaptive bust should be large enough. However, it is also pretty tedious to individually change the parameter of each point to get the good value of the bust. It is always good to change few reference points to change the surface and volume of the entire bust. This will definitely speeds up the trial and error process in order to conceive the right surface for the new volume breast. This can be achieved by relating the different point with each other. On this study we tried to relate the other point in reference to the first point of the curve, for example as shown in table 3 for 95B bust size.

Table 3. Relating the parameters of the different point of 95B size

| Description               | Curve Name | Point references | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---------------------------|------------|-----------------|---|---|---|---|---|---|---|
| 1st Horizontal Curve      | HC1        |                 | 10| 10| 10| 10| 10| 10| 10|
| 2nd Horizontal Curve      | HC2        |                 | 10| 10| 10| 10| 10| 10| 10|
| 3rd Horizontal Curve      | HC3        |                 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| 4th Horizontal Curve      | HC4        |                 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| 5th Horizontal Curve      | HC5        |                 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| 6th Horizontal Curve      | HC6        |                 | 10| 10| 10| 10| 10| 10| 10|
| 7th Horizontal Curve      | HC7        |                 | 10| 10| 10| 10| 10| 10| 10|
| Out Line points           | LC (all equal) |               | 5.5| 5.5| 5.5| 5.5| 5.5| 5.5| 5.5|

In similar trend, we conceived the bust sizes of 90B, 90C, 90D and 90DD with the change in parameter as shown in Figure 19. For realizing those different volumes of the bust sizes of 90, we used the initially realized adaptive bust, 95B size.
While realizing the new volumes of bust we need to aware two things. First, if we want to change the sizes of the bust, i.e. 80, 85, 90, 95, 100, etc., the parameters of the outline of the bust has to change. This change will define the cup size of the bust size which is responsible by the changing of the surface point parameter. The second one, even if the change of the parameter is relative while conceiving new volumes of bust, few point parameters need to be changed to get smooth and accurate surfaces.

4.2. Comparison of 3D/2D pattern with traditional 2D pattern
The 2D traditional bra pattern for cup size 90B using the theoretical (standard) measurement [9] has been developed. By using the traditional 2D pattern making, the final shape of bra pattern for 90B standard size is presented Figure 20. For comparison, the flattened 2D/3D patterns for cup size 90B from respective 3D adaptive mannequin were also introduced (Figure 21).

As you see in Figure 22, the result of the patterns conceived in 2D for size 90B and the patterns conceived in 3D for bust of size 90B are more or less similar, we can say we have a good result at hand. After comparing and adjusting with the standard 2D pattern the size of the adaptive bust can now be changed and the patterns will change relatively as well.

5. Conclusions
In this particular study the testing of the adaptive corset with changes of parameters to conceive varying volumes of the bust revealed that using good parameters was all required to get the bust of a correct size. Conceiving the 3D patterns on the 3D bust and then comparing it with 2D patterns also gave a satisfactory result. Determination of this different volume of breast will help us for the developments of customized female bullet proof vests by punching method with the same volumes of breast to accommodate the bust area. This will enhance the fitness as well as the ballistic performance which was affected by the traditional cut and sew methods. However this research needs further study in terms of establishing the equation that determines the change of parameters with the change in the cup size. This parametric equation will reduce the tedious procedure to change the parameter and the trial and error methods to conceive the different adaptive bust. A detailed study in this direction will help us also to define parameters and obtain a perfect customized corset surface as well.
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