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An Iterative and Anthropometrically Driven Approach to Body Armor Plate Design for Females

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ABSTRACT

This paper presents an iterative and anthropometrically driven approach to design an armor plate for females. The current US Army body armor plate shapes were originally developed for male torso shapes. As females' roles in the military change and their need for protective plates increases, it becomes important to ensure they are adequately protected. An initial design of the plate shape was based on a female torso shape analysis of 3D body scans from the 2012 US Army Anthropometric Survey (ANSUR II). Further iterations of the design were based on rapid prototyping and quick fit evaluations of the prototype plates focused on user feedback, impacts on gross mobility and user comfort. Four rounds of user testing and redesign were conducted, identifying a plate shape for medium breast sized females. The evolution of plate shape reflects a more realistic adaptation of deformed breast shape under comfortable pressure.

Keywords: Female torso shape, Body armor plate, Fit evaluation, Rapid prototyping, Female armor

INTRODUCTION

The opening of combat arms positions to females, combined with innovative manufacturing processes allowing for increased curvature in rigid ballistic plates, offers the opportunity and need to develop a body armor plate designed specifically for the female body. The current US body armor plates were developed based on male torso shapes. While some earlier efforts have focused on increased curvature for female torso shape, manufacturability was always a concern. Additionally, it's unclear how best to define the plates' shape to fit the complex curvature of the female torso. Two questions are frequently asked: how many different plate shapes are required to cover the spectrum of female torso shapes and how to correlate female torso shapes to plate shapes.

A few studies have been dedicated to investigating female body armor fit and products focused on fit improvement. Assessment of existing body armor fit was reported in An (2011), Choi et al., (2017), and Coltman et al. (2020, 2022a); they suggested that the existing body amor sizing system is inadequate for female soldiers. Coltman et al. (2022b) further studied the impact of female torso/breast's anthropometric characteristics to body armor fit. Their study suggested, for large breasted female soldiers, a different curvature of armor plate may be necessary to accommodate their larger breast volume than the standard issue. Abtew et al. (2018) and Yang (2011) discussed female breast shape based on soft armor design and material selection respectively. West (2019) designed a hard plate shape to accommodate breast volume, but only for one test participant. In all, it is evident that both the size and shape of existing body armor systems cause fit problems for females.

This paper presents an iterative design approach to developing a female specific plate shape(s) based on the 2012 US Army anthropometric survey data (ANSUR II, Gordon et al., 2014) and following iterative refinement of the design based on rapid prototyping and fit evaluations. The fit evaluations are focused on user feedback, gross mobility, and comfort. It also provides insight into how the original plate shape was selected and defined, as well as how it evolved from a rigid dramatic curved body shape to more realistic, subtle curvature allowing for deformation of the breast and an improved level of comfort from the pressure. Overall resulting in an acceptable plate curvature for females with a medium size bust.

TORSO SHAPE ANALYSIS AND INITIAL PLATE DESIGN

Female Torso Shape Analysis

Li and Mitchell (2023) identified nine torso shape groups among 1646 female subjects (age 17 ~ 58, BMI 16.4 ~ 40.8) based on the ANSUR II 3D scan database (Gordon et al., 2014). The definition of those shape groups and their distribution is shown in Figure 1 and Table 1.

Based on the torso shape classification, we used a single angle value to quantify the breast curvature (Figure 2). This angle is formed by two lines, one line follows the surface slope from the Suprasternale toward the apex, and the other line connects the apex and the abdominal protrusion. The angles of the nine torso shapes are measured and displayed in Table 2. Then, we grouped breast curvatures into three groups: large, medium and small curvatures. The groupings are roughly based on the large angle gap between shapes. It is found that the shape A could be accommodated by the currently issued armor plate, which has a 21 degree angle at its sagittal plane. However, the medium and large curvature groups are assumed to require additional curvature in the plate to accommodate these larger breast shapes. From each curvature group, the shapes with the largest angle (M for medium & V for large) were selected to represent its group (Figure 2 and Table 2).

Initial Plate Shape Design

The initial design of the medium and large curvature plates was based on torso shapes M and V which have curvature angles of 33 and 44 degrees, respectively (Figure 2 & Table 2). First, we obtain the front surface regions of the M and V torsos (Figure 2). Using Geomagic Design X (Rock Hill, SC USA), six torso cross-sections were selected for surface lofting as shown in Figure 3.

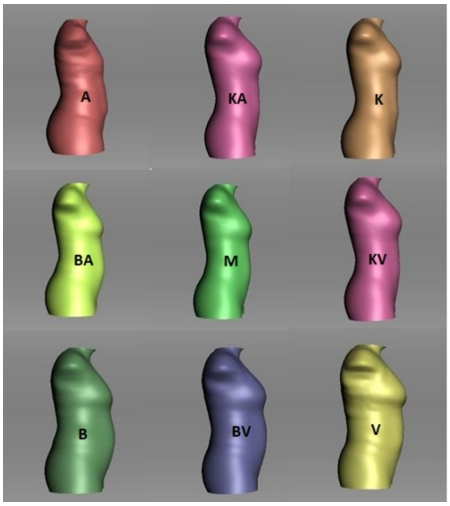

Figure 1: Side view of nine female torso shape groups (courtesy of Li & Mitchell, 2023).

Table 1. The definition of nine torso shape groups based on Chest-Waist (CW) drop and Waist-Buttock (WB) drop (courtesy of Li & Mitchell, 2023).

Shape Label	Description	Percentage of Sample (N = 1646)
M shape	A shape of both drops within one standard deviation from their means	51.5
K shape	Curvy shape with both large drops	4.8
V shape	Invert triangle shape with large Chest-Waist Drop and small Waist-Buttock Drop	0.7
A shape	Triangle shape with small Chest-Waist Drop and large Waist-Buttock Drop	0.5
B shape	Straight (barrel) shape with small drops	6.1
KA shape	Shape between A and K	9.3
KV shape	Shape between V and K	9.7
BV shape	Shape between B and K	8.4
BA shape	Shape between A and B	8.7

While the number of cross-sections defines the conforming degree in each vertical torso shape, the number of control points of each cross-section will define the shape at the horizontal section. The more slices and more control points that are adopted, the more details the 3D torso shape will preserve. For the cross-sectional shape of the plate, it is not desirable preserve too much details, for example the concave geometry between breasts (Figure 4). Therefore, to make a convex cross-section at the bust level, while also preserving the horizontal shape for the other parts of the torso cross-sections, six control points were deemed sufficient.

Similarly, the placement of the cross-sections is critical to the development of the plate's vertical shape. It is not desirable for the plate to have a concave crease at the under-bust. This is because the lowest part of the concave portion was anticipated to cause discomfort, depending on the breast location.

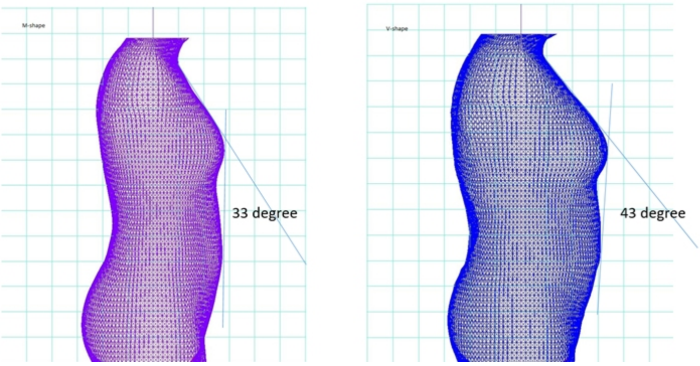

Figure 2: Angular measurement of breast curvature from frontal torso profile for the M shaped torso (purple, left) and the V shaped torso (blue, right).

Table 2. Angles of front torso profile among nine torso shapes.

Torso Shape		Angle (degree)	Shape distribution (%)	Subtotal (%)
Large Curvature	V*	44	0.7	23.6
	KV	43	9.7	
	BV	41	8.4	
	K	39	4.8	
Medium Curvature	M*	33	51.5	75.6
	KA	32	9.3	
	B	32	6.1	
	BA	29	8.7	
Small Curvature	A	25	0.5	0.5

*indicates that torso shape was selected as the representative torso shape for the curvature group.

Hence, the six cross-sections located as shown in Figure 3 will maintain a smooth, nearly convex vertical profile for the plate. Two plates, one corresponding to the M torso and one to the V torso shape, were created and 3D solid models were developed (Figure 5). Between those two plates, the medium curvature plate was 3D printed for the fit evaluation.

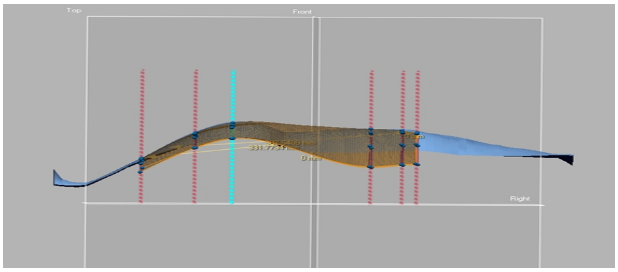

Figure 3: The selection of torso surface cross sections (vertical dash lines) for generating a lofted surface.

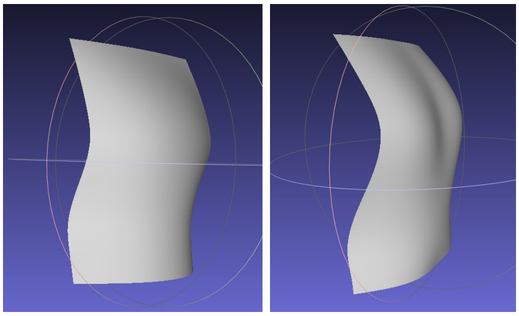

Figure 4: Surface shape of medium plate, six control points (left) and seven control points (right) on the M shape.

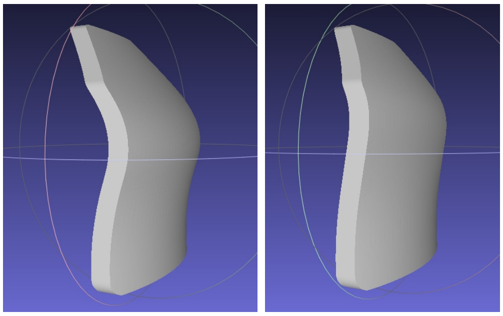

Figure 5: 3D solid models of high curvature (V shape, left) and medium curvature (M shape, right) plates.

The decision was made for these prototypes to focus on the form factor and therefore were not weighted to match either the current plate or anticipated weight and weight distribution of the prototype plates. This was done for cost savings and scheduling; and focusing on the form factor (i.e., curvature) and fit. The baseline plate (currently fielded armor plate) was also 3D printed without additional weight added, for a fair comparison point.

FIT EVALUATION–REDESIGN CYCLE

The fit evaluation data collection was simplified to record subjective responses and comments from test participants (TPs) on three questions, 1) does the plate fit, 2) is the contact pressure even, and 3) are there any spots of discomfort when the TP positions the prototype plate on her chest. This simplification of the data collection was utilized to allow for a very quick, iterative, focused assessments. Total testing duration was less than five minutes per prototype plate. No anthropometric dimensions were taken, but self-reported brassiere size was collected to quantify TP's breast size and volume. Once all prototype plates were assessed, TPs were asked to rank them, based on their preference and comfort level. Some TPs participated in multiple iterations. Following the design-fit-redesign cycle, additional prototype plate(s) were made for each test round. The fit evaluation was continued with all prototype plates made, in other words the former round of prototype plates were included in the subsequent fit tests.

First Iteration Prototype Fit Evaluation and Redesign

In the evaluation of the first iteration prototype, a total of four female TPs volunteered and tested the medium curvature plate along with a 3D printed, prototype version of the currently issued armor plate, the Enhanced Small Arms Plate Insert (ESAPI). Their brassiere sizes were 34C, 34D, 36C, and 38C. Given the most populated brassiere size from the ANSUR II database is size 34D (Choi-Rokas, 2022), and the breast volume between 34D and 36C are equivalent (with different band sizes) (Choi-Rokas et al., 2022), the team felt it was appropriate to classify all four TPs as having a medium sized breast and therefore they tested the medium curvature plate.

TP feedback determined that the medium curvature plate was too curvy for all the medium breasted TPs. When TPs positioned the plate against their breast, they pressed it firmly against their front torso, the top edge of the plate caused pain and discomfort to their sternum while the apex of their breast only touched the inner surface of the plate lightly. Because the breast is composed of soft tissue, compared to the sternum, it allows the flatter plate shape to create a more even pressure on the breast and sternum. Therefore, for the second iteration of design, the new plate's curvature will be reduced.

To understand better how much curvature reduction may be acceptable from a user perspective, the findings from Choi-Rokas et al. (2022) were revisited. In that study, females were measured in a series of different commercial sports brassiere's, the authors calculated a difference of approximately 20mm of Chest Depth, when measured at the breast apex, while still maintaining a comfortable level of compression. Thus, it was considered that a 20mm reduction at the highest peak point of the prototype plate may reduce the pressure on the top edge of the plate (Figure 6). The original (first round) plate has an apex of 45mm (thereafter the 45mm plate); therefore, the new plate's apex was reduced by 20mm, giving it an apex of 25mm (thereafter the 25mm plate). Figure 6 illustrates the plate apex heights and overall shapes.

Second Iteration of Prototype Fit Evaluation and Redesign

For the second iteration of fit testing TPs wore the 25mm, the 45mm, and the 3D printed ESAPI plates. A total of seven TPs volunteered in the second round of testing. The TPs' brassiere sizes were 34C (n = 2), 36C (n = 2), 38C,

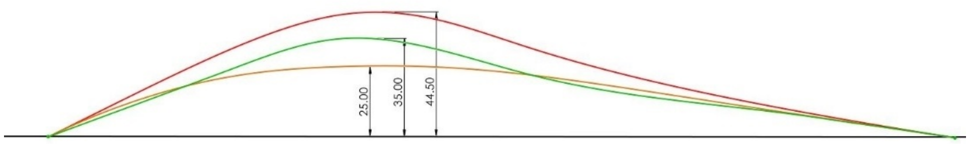

Figure 6: Modification of plate shape from peak height of the cross section at the middle (sagittal) plane. Yellow is the 25mm plate (2nd iteration), Red is the 45mm plate (1st iteration), Green is the 35mm plate (4th iteration).

36DD and 40DD. Of the three prototype plates (ESAPI, 25mm and 45mm), the 25mm plate was ranked the highest by TPs with medium sized breasts, and the 45mm plate was ranked highest by the large breasted TP.

Although the 25mm plate seems to provide adequate height and space for the TP's breasts, the TPs reported that the top edge of the plate caused discomfort and high contact pressure against the sternum. Therefore, it was decided for the third iteration prototype to curve or flare out the top and bottom edge of the 25mm plate, as shown in Figure 7 in yellow (thereafter the curved edge 25mm plate).

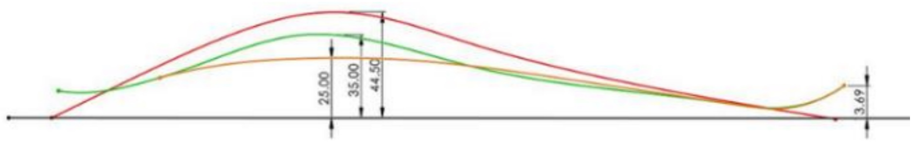

Figure 7: Modification of plate shape from peak height of the cross section at the middle (sagittal) plane and curved out edges for the 25mm (yellow) and 35mm (green) plates, the 45mm (red) plate profile is used as a reference.

Third Iteration of Prototype Fit Evaluation and Redesign

The curved edge 25mm plate was not tested on multiple TPs, but one whose brassiere size is 34C. When the curved out 25mm plate was positioned on her chest, it was immediately apparent that the apex of the new plate had been reduced. It effectively provided less volume to accommodate the medium sized breast than the original 25mm version, although the curvatures between the two plates are identical. As a results, the curved edge 25mm plate felt very similar to the ESAPI in that it had a smaller curvature in vertical profile. Based on this result, the prototype was revised to increase its volume accommodation by increasing the plate's peak height to 35mm, while keeping the same curved out edges as the third iteration plate (thereafter the curved edge 35mm plate) (green line in Figure 7).

Fourth Iteration of Protype Fit Evaluation and Redesign

For the fourth iteration of fit evaluation, the 45mm plate was also modified to have a curved out top and bottom edges. Then, the three plates with curved edges (25mm, 35mm, 45mm) were tested together with ESAPI plates.

A total of 6 TPs volunteered. Their brassiere sizes were 34B, 34C, 36A, 36B, 38A, and 38B. Each participant was asked to rank order the plates. The curved edge 35mm was the first choice for five TPs. The other TP (36A) selected the 25mm plate as her first choice. The TPs' second choices were split between the prototypes. Three TPs (34B, 34C, 38A) selected the 25mm plate, two TPs (36B, 38B) selected the 45mm plate, and one (36A) selected the ESAPI plate. None of the TPs reported feeling any discomfort at the top edge of the curved edge 35mm plate.

CONCLUSION AND DISCUSSION

This paper outlines a methodology for the development of an anthropometrically driven rigid plate shape and ways to quickly and iteratively assess and improve upon that design through the incorporation of fit testing and user feedback. When designing an armor plate from 3D scan images, it is still necessary to get feedback from users to account for the soft tissue deformation and to simulate realistic wearing of the plates, rather than relying on the rigid shape created by the body scan. During this study, a total of four design-fit-redesign iterations were performed. The critical outcomes through this process are two-folds: 1. when tracing the curvature from the scan surface to construct the curvature on the front plate, the apex of the plate at the breast area should be flatten (i.e., 35mm plate is created by reducing peak height 10mm from original curvature) to mimic the effect of the deformed breast under the plate; 2. the curved-out edges on the top and bottom of the plate reduced the pressure substantially at the sternum, while also decreasing concerns of potential injury due to pressure at different postures (e.g., prone). Based on the iterative design and testing, the 35mm curved edge plate was selected as the recommended shape for the medium breasted females. Figure 8 shows the 25mm and 35mm plates aligned to M torso shape in the vertical cross-sectional view and 3D view, respectively. The curvature of those two plates, in terms of the angular measurement, are approximately 25 degrees for 25mm plate and 30 degrees for 35mm plate.

Future work will focus on defining the accommodation envelope of fit for the fourth iteration prototype through testing with a much larger sample of participants. A detailed analysis of the torso profile angle distribution and breast size may be necessary to correlate the plate shapes to torso shapes. This will allow us to delineate the anthropometric range of each plate in the target population, based on a user's breast size. While this current work touched on the plate shapes required for medium breasted women, additional fit testing and design work needs to be done to ensure that the large curvature plate will be accommodate large breasted females, who account for 24% of the Army's user population. Furthermore, the current design process does not take the body armor carrier and soft armor into account, which may have significant impacts on the acceptability of plate shapes and curvatures.

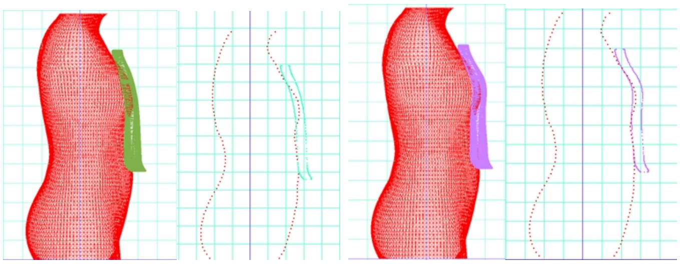

Figure 8: The curved edge 25mm plate (left) and the curved edge 35mm plate (right) aligned to M torso shape in 3D view (red torso) and vertical cross-sectional view (clear torso).

Once this work has been completed and a family of plate shapes has been developed, a full fit evaluation of the complete body armor system should be undertaken.

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