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Posted Date: 24 June 2024

doi: 10.20944/preprints202406.1604.v1

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Development of Ballistic Protection Soft Panels According to Regulatory Documents

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Abstract: The development of ballistic protection vests (BPVs) has become increasingly significant, particularly in the design of soft panels, which are critical to the overall size and configuration of these vests. Despite their importance, a standardized design process for soft panels is lacking in the literature. This research addresses this gap by creating soft panels tailored to the body types of regional soldiers while adhering to relevant standards. We propose a comprehensive design algorithm and evaluate the applicability of the National Institute of Justice (NIJ) standard 0101.06 test templates for configuring these panels. This study aims to design soft ballistic panels for BPVs that cater to the body type requirements of regional soldiers and comply with NIJ 0101.06 standards. We have developed an algorithm for designing soft panels and analyzed the feasibility of using NIJ test templates for their configuration. The research encompasses a detailed literature review, analysis of existing BPV soft panels, and comparison with NIJ test templates. The panels were designed and scaled using computer-aided design (CAD) systems and evaluated through by physical fitting on mannequins and virtual fitting using the Clo3D program. Our findings indicate that the NIJ standard test templates are only partially applicable to the design of soft panels. The developed methodology includes an algorithm and size specifications tailored to regional covers. A coefficient (K) was identified to calculate the soft panel surface area prior to design, thereby saving time and resources.

Keywords: Ballistic protection vests; soft panels; body armor; design; NIJ standards

1. Introduction

The development of individual BPVs is critical globally due to the high demand in both civil and military defense sectors [1,2]. With the advent of new textile materials and enhanced soldier equipment, the design and modularity of ballistic protection clothing must evolve to integrate effectively with personal protective equipment (PPE). Modern BPVs must comply with NIJ standard 0101.07, widely used among NATO member states, to ensure optimal protection and comfort. This research focuses on creating BPVs with enhanced modularity and adaptability, considering the diverse body types of the target audience while maintaining compliance with NIJ and STANAG 2335 standards.

Ballistic protection vests (BPVs) must meet the stringent requirements of modern personal protective equipment (PPE) [3]. One of the critical requirements is the full-fledged modularity of BPV components while ensuring compliance with the National Institute of Justice (NIJ) standard 0101.07 [4], the most widely used standard among NATO member states. This standard not only mandates a high level of ballistic protection but also emphasizes maximum comfort for the wearer. Enhancing the physical comfort and mobility of the wearer can be achieved through flexible BPV construction and design, task-specific compliance, weight reduction, and the creation of BPVs tailored to specific sizes, accommodating various body types within the target audience.

The primary functional components of a BPV are the soft panel and the hard plate, both of which provide critical protection against ballistic impacts. The size and features of a BPV are predominantly determined by its soft panel. According to the National Institute of Justice Selection & Application Guide 0101.06 [5] to Ballistic-Resistant Body Armor, “The standard does not dictate how armor must be designed; rather, it prescribes what it must be able to do. This ensures that body armor meets officers’ needs, yet leaves manufacturers free to innovate.” Furthermore, the guide states, “To provide for uniformity in testing, the standard provides five template sizes for soft armor panel samples (C1, C2, C3, C4, and C5). These templates are designed to represent 95% of officers, although they are not indicative of service armor design and are required for testing purposes only” [5]. This implies that the only design parameter of the NIJ standard test templates that is relevant to manufacturers is the surface area of the production panel.

Given that the surface area of the panel is significantly influenced by the primary parameters of the soft panel—length and width—and that the GUIDE [5] claims the test templates are intended to cover a wide range of officers, this study aims to determine the feasibility of using NIJ standard test templates, adapted to human body proportions, as the basis for BPV soft panels. Additionally, it seeks to investigate whether other manufacturers have utilized these test templates in their design solutions.

The primary objective of this research is to develop soft panels suitable for the body types of regional soldiers across all necessary sizes, ensuring compliance with NIJ [4,6] and STANAG 2335 ("Interchangeability of Combat Clothing Sizes") standards [7].The goal is to achieve an optimal balance between ballistic protection and physical comfort. This study explores the possibility of using test templates in BPV design and develops a soft panel design methodology that could be employed by manufacturing and research companies for pattern making.

Currently, no comprehensive methodology exists for designing soft panels that adhere to these standards and potentially saving companies considerable time in locating relevant information and ensuring compliance with minimum requirements without extensive research. Often, companies may bypass the research phase to expedite design, relying on existing market panels without fully understanding the correlation between parameters and human body proportions, thereby compromising both the physical comfort and ballistic protection of the BPV.

This methodology can also be valuable for researchers focusing on improving soft panels and BPVs in aspects beyond size fitting. The study involves analyzing regulatory documents and technical information on globally produced soft panels, designing soft panel patterns for specific regions, fitting them on appropriate figures, and assessing their compliance with standard requirements. The proposed methodology's broad applicability was on 16 different BPV sizes in two variations: as an outer garment and as an undergarment.

The development of a standardized methodology for soft panel design not only facilitates compliance with regulatory standards but also enhances the efficiency and effectiveness of BPV manufacturing. By ensuring that soft panels are tailored to the specific body types of regional soldiers, this research contributes to the creation of more comfortable and protective BPVs, ultimately improving the safety and performance of military personnel.

2. Materials and Methods

This research was initially based on the NIJ 0101.06 standard [6]]and later evaluated against the updated NIJ 0101.07 standard [4]. The methodology comprises several key steps:

1. Literature Review: Conducting an extensive review of existing standards and BPV soft panel designs.
2. Pattern Design: Developing and scaling soft panel patterns using CAD systems, based on the typical measurements of regional soldiers.
3. Fitting Evaluation: Assessing the patterns through physical fitting on mannequins and virtual fitting using the Clo3D program.
4. Algorithm Development: Formulating an algorithm for soft panel design, incorporating necessary improvements and adjustments identified during the fitting process.

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5. Comparative Analysis: Comparing the surface areas of NIJ test templates with the designed panels to evaluate their applicability.

The study aims to assess the suitability of NIJ test templates for BPV design and to develop a standardized methodology for the production of soft panels, thereby saving time and resources for manufacturers and researchers.

This research was conducted based on the NIJ 0101.06 standard and its updated version NIJ 0101.07 released in October, 2023. Consequently, the designed panel patterns and methodology were reassessed to ensure compatibility with the updated standard. Despite supplementations in NIJ 0101.07, such as improved test methods for designing women's BPVs, more rigorous testing of soft panels, and references to standardized test methods and laboratory practices, it was determined that there were no significant changes affecting soft panel pattern design. Although the NIJ 0101.07 standard does not specify the surface area for production soft panels, it retains the same test template sizes and configurations. The standard states, "…the supplier selects the templates to be used based on the range of sizes over which the armor model will be produced". This necessitates comparisons between production soft panels and NIJ test templates, particularly in terms of surface area. For this research, test templates from the NIJ 0101.06 standard were utilized due to their convenient metric measurements, which are not included in the NIJ 0101.07 standard.

BPV Types and Design Recommendations

According to the NIJ standard, two types of BPVs can be distinguished based on their usage: undergarment BPVs, designed to be concealed and typically consisting only of soft panels, and outer garment BPVs, which may include hard plates for additional protection depending on the required protection level. Outer garment BPVs can also incorporate various elements and accessories necessary for specific work duties. Unlike the NIJ standard, which primarily focuses on requirements and performance, more specific recommendations for BPV design and body interaction points are found in the GUIDE and are summarized in Table 3. For instance, the frontal panel shall start at the nape of the neck and extend to 2-3 finger widths above the waistline. The GUIDE also explains the use of the proposed C1-C5 test templates. The width and length gradation step were defined using the STANAG 2335 standard, adopting the unified size designation—an 8-digit code for more precise size comparison between member states [7].

Analysis of Existing BPV Soft Panels

The study included an analysis of BPV soft panels currently used by the national army, involving a pattern comparison of sample parameters with NIJ standard test templates in both printed and CAD formats. The surface area corresponding to each test template was used to determine the characteristics of the soft panels and to assess whether the proposed NIJ standard test templates and requirements were considered in their design [5,6].

Data Collection and Adaptation

Due to the absence of up to date information on regional soldiers' body measurements, national literature from previous periods was reviewed [8,9] and measurement tables from global BAV companies [8,10–18] were surveyed. In collaboration with a local military clothing manufacturing company, these measurement tables were re-worked to reflect the current situation in the region.

Determining Ease Allowances

Seven different layers of military clothing were placed on a size-appropriate mannequin to measure the differences between and uncoated and a clothed mannequin in chest and waist circumferences. This helped to determine the required ease allowances for the outer garment and undergarment BPVs [19].

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Design and Fitting Evaluation

The soft panel patterns were designed and scaled using a CAD system based on typical regional soldier measurements. Fitting evaluations were conducted on an adjusted mannequin and virtually using the Clo3D CAD system's fitting module. The suitability of the patterns for different sizes within the target audience was assessed. All improvements and changes identified during the fitting process were analyzed and digitally incorporated into the soft panel patterns in the CAD system.

Development of Design Methodology

The design methodology was developed as an algorithm, incorporating all necessary improvements, analyzing them, and summarizing the development progress of the soft panels. This comprehensive methodology aims to assist companies in saving time and ensuring compliance with minimum standards without extensive research. It also serves as a valuable resource for researchers focusing on aspects of soft panel and BPV improvement beyond size fitting.

3. Results and Discussion

The research reveals that although NIJ standard test templates provide a useful starting point, they are only partially applicable to the design of soft panels. Our proposed algorithm and size specifications for the region ensure a more precise and tailored fit. By identifying a coefficient (K) for calculating the soft panel surface at the pattern development stage, the study offers a practical tool for optimizing the design process, thus enhancing efficiency and resource management.

Determination of Research Data

BPV design criteria can be divided into three groups: ballistic energy absorption, wearer comfort and mobility, as well as product accessibility. When designing BPV, including their soft panels, demanding tasks such as: maximum absorption of ballistic energy, comfort of the wearer, usability, compliance with regulatory documents, reduction of the total weight of the product, flexibility of the design, and reduction of product costs must be solved (see Figure 1) [5–7,20,21].

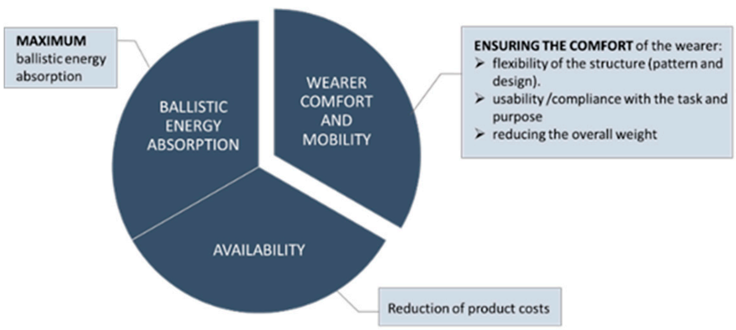

Figure 1. BPV design criteria and tasks (author's image).

To improve the physical comfort and mobility of the designed BPV, the level of protection must be first determined. The speed of the bullet can reach 398–990 m/s and impacts the body with different forces; therefore, each BPV is designed for a specific level of protection [22]. The NIJ 0101.06. standard [6] distinguishes 5 levels of protection from IIA to IV levels, where IIA is the least ballistic energy absorption. Each subsequent level can also protect against the threat of the previous levels. Since October 2023, there is a separate NIJ Standard 0123.00 for the ballistic protection levels and associated test threats [22]. The BPV developed within this research was designed for level IIIA, which according to new standard is NIJ HG2, as this is the highest level for which the necessary protection can be achieved only with soft panels. The protection levels according to NIJ are presented in Table 1.

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Table 1. NIJ standard BPV protection levels [22].

Protection Level	Former Threat Level	Test Threat	Reference Velocity, m/s
NIJ HG1	NIJ Level II	9mm Luger FMJ RN 124 grain .357 Mag JSP 158 grain	398 436
NIJ HG2	NIJ Level IIIA	9mm Luger FMJ RN 124 grain .44 Mag JHP 240 grain	448 436
NIJ RF1	NIJ Level III	7.62x51mm M80 Ball NATO FMJ Steel Jacket 147 +0/-3 grain 7.62x39mm MSC Ball Ammunition Type 56 from Factory 31 5.56mm M193 56 +0/-2 grain	847 732 990
NIJ RF2	NA	7.62x51mm M80 Ball NATO FMJ Steel Jacket 147 +0/-3 grain 7.62x39mm MSC Ball Ammunition Type 56 from Factory 31 5.56mm M193 56 +0/-2 grain 5.56mm M855 61.8 ± 1.5 grain	847 732 990 950
NIJ RF3	NIJ Level V	30.06 M2 AP 165.7 +0/-7 grain	878

Depending on the protection level, size, and type, an assembled BPV can weigh between 3 and 25 kg. A higher level of protection can be achieved by increasing the number of layers of soft panels and adding hard plates, as well as other additional protective parts (shoulder, neck, upper arm, throat, groin, etc.). These measures results in a heavier and less flexible BPV assembly, interfering with the soldier's daily tasks [6,21].

BPV Physical Comfort

The product's functionality is critical for the soldier's efficiency and is closely related to the number of layers of clothing worn underneath and the amount of equipment that can be attached to the BPV. Functionality is determined by the work tasks to be performed by wearer and the actions required for their completion; for example, it could be an ability to quickly change the layers of clothing worn underneath, run, bend, and squat freely, stand in battle positions, and so on [23]. When designing the soft panel configuration, it is necessary to pay attention to physical comfort, which is directly related to freedom of movement and coherence with the body surface.

In order to choose suitable anthropometric data for the specific product, it is essential to identify which parts of the body and to what extent will be covered by PPE, what physical activities and how long to be performed by the wearer [21].

The freedom of movement can be evaluated in field experiments, for example with a worn prototype trying to walk, sit, climb, run, pick up an object from the floor, or simulating the movements that are necessary for a soldier's everyday life, such as placing a weapon on the shoulder and throwing a grenade.

For example, the important body measurements for the design of shoulder garments is the width of the shoulders, because when raising the arms up, for a soldier decreases by 4.6–5.8 cm. While the width of the armpits when extending the arms forward, increases by 9.3 cm [23]. This example clearly demonstrates that changes in body measurements during movements must be considered in the patternmaking of soft panels.

Dimensions of Soft Panels

According to the NIJ 0101.06 standard, the basic characteristic of soft panels is their surface area. The NIJ standard [6] defines three different area limits for each panel size:

- the first ballistic test template surface area with a very accurate configuration, according to which soft panels are prepared for ballistic protection tests;
- the second and third are the maximum and minimum surface areas for production soft panels to be placed in protective vests, specifying only their configuration with specific indications about panel overlapping in the side parts and indications ensuring the ergonomic comfort of the BPV wearer in the neck, waist, and arm areas.

Table 2 presents the main characteristics of the soft panel test templates under NIJ standard. According to these, the proposed test templates were verified whether they can be adapted to the human body and used in panels' production. As well as other manufacturers' soft panels were compared whether they adhered to them in their designs.

Table 2. Summary of the main characteristics of NIJ Standard test templates [6]

	Surface area, mm²		Width (A), mm		Height (B), mm		Upper part width (C), mm	
	min	**max**	A_{min}	A_{max}	B_{min} (Front/Back)	B_{max}	C_{min}	C_{max}
NIJ-C1	<98000	98000	292.2	317.5	262.9 / 292.1	317.5	228.6	254
NIJ-C2	98000	139900	406.4	431.8	313.7 / 342.9	368.3	254	279.4
NIJ-C3	139900	189000	520.7	546.1	364.5 / 393.7	419.1	279.4	304.8
NIJ-C4	189000	245500	635	660.4	415.3 / 444.5	469.9	304.8	330.2
NIJ-C5	245500	>245500	749.3	774.7	466.1 / 495.3	520.7	330.2	355.6

The GUIDE [5] contains suggestions for the selection of BPV and indicates of exact points where the soft panels need to start and end on the soldier's body, which also helps in the designing of the soft panels. For example, the front panel must start directly from the jugular notch and end 4.45–6.67 cm above the working belt. All the requirements specified in the document supplementing the NIJ standard [6] regarding the side cover of the panels and the indications ensuring the physical comfort of the BPV wearer in the neck, waist, and arm areas are summarized in Table 3.

Table 3. The GUIDE [5] requirements regarding the design and use of soft panels in BPV

No.	Requirement	Front panel	Back panel	Instructions for outer garment BPVs
1.	Side coverage	Front and back panels overlap at least 5.08cm on the each side.		-
2.	Height	Should extend from just below the jugular notch to two to three finger-widths above the top of the belt when standing.	Should extend from approximately 5.08cm below the collar to approximately 2.54cm above the belt.	Can be slightly longer without impeding movement or comfort.
3.	The armpit area coverage	Ballistic coverage under the arms should be as high as possible without compromising the ability to obtain a shooting position.		May afford slightly greater protection in this area.

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4.	Surface area	The minimum and maximum specified in the NIJ standard must be maintained.	A larger area of the body should be covered, and more protection should be provided.
5.	Fit	Should fit snugly, but not so tightly that it may affect breathing (including deep breathing, such as may occur during a foot chase). The armor should slide slightly on the body as the torso is rotated back and forth.	Less tight / looser
6.	BPV and soft panel physical comfort check	When trying on the soft panels and BPV itself, soldiers must conduct various daily movements, such as rotating their upper bodies or sitting down, to ensure that the soft panels are not "sitting" on the belt and the upper edge is not pressing against their neck.	

Taking into account the above summary, the soft panels were configured using the dimensions C and D of the relevant size test template from Figure 2 of this article, covering the entire minimum border area of the upper part of the test template. Dimension A changes depending on the chest and waist circumferences of the human body, which are supplemented with the constructive allowances (undergarment BPV: 1-4 cm, outer garment BPV: 3–7 cm) and the side coverage width, while dimension B changes according to the human body's height.

These dimensions also serve as features of the soft panels that are going to be created, allowing us to analyze their compatibility with the proportions of the human body. Figure 2 illustrates the locations of all dimensions on the soft panel.

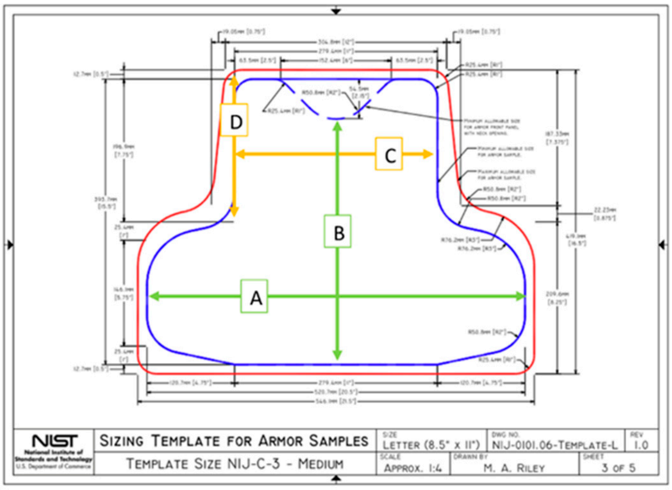

Figure 2. NIJ C3 Test Template [6] for soft panels with the main dimensions marked, where A is panel width, B is panel height, C is panel upper part width, and D is panel upper part height. The blue line indicates the test template's minimal parameters, while the red line indicates the maximum.

Configuration Analysis of Production Soft Panel Samples Used in the Military

In order to improve the BPVs and soft panels used in a certain region, it is necessary to understand the product range and configurations that are already in use; therefore, an analysis of available soft panel samples was carried out.

Soft panel patterns from two manufacturers, "Company A" and "Company B," were studied and analyzed to determine their conformity with the requirements of NIJ standard 0101.06 [6] and the indications of accompanying documents [5], presented in Tables 2 and 3, and Figure 2.

The First Requirement: Surface Area

Table 4 shows the analyzed soft panels according to their surface area which adheres to a specific NIJ standard [6] template. The study determined that the analyzed BPV samples did not cover all test templates; only soft panels of NIJ-C3 and NIJ-C4 sizes were available for the sample assessment.

Table 4. Adherence of the analyzed soft panels to test templates NIJ-C3 and NIJ-C4

Title 1	Allowable surface areas for production BPV, min-max, m²	Manufacturer, name of the analyzed soft panel.	Size	Type of wear	Surface area, m²		Height, cm		Width, cm	
					Front panel	Back panel	Front panel	Back panel	Front panel	Back panel
NIJ-C3	0.1399-0.1890	"Company A", S1	S1	Outer garment	0.1710	0.1436	34.3	36.6	64.6	52.2
		"Company A", S2	S2		0.1770	0.1635	36.6	39	64.8	59.4
		"Company A", S3	S3		0.1832	0.1838	39.2	41.9	64.6	66.8
		"Company A", paper	S1/S2		0.1635	0.1505	36	38.5	61	56.8
		"Company B", no.39/57, no.37	S2		0.1675	0.1651	35.7	38.7	61.5	62
		"Company B", no.15/16, no.13/14	LL	Undergarment	0.1523	0.1639	37	44	54.5	56.8
NIJ-C4	0.1890-0.2455	"Company B", no.27	2XLL	Undergarment	-	0.1999	-	49	-	64.5

In total, 16 samples of soft panels were examined – 5 outer garment BPV soft panel sets, 2 undergarment BPV soft panel sets, and 1 undergarment BPV back panel.

In comparison the areas of the outer garment BPV size S2 soft panels of both manufacturers, showed minimal differences: 0.0095 m² for the front panel, and 0.0016 m² for the back panel. Only the surface area configuration of the comparable panels differed (see Figure 3).

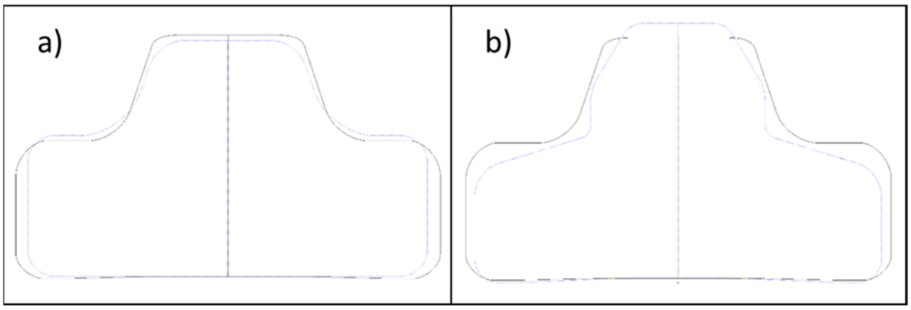

Figure 3. Front (a) and back (b) panels of outer garment BAV size S2 – "Company B" (blue dashed line) and "Company A" (black line).

The Second Requirement: The Configuration of the Soft Panels

To determine whether these companies used the dimensions from the relevant test templates specified by the NIJ standard, all three dimensions A, B, and C (see Figure 2) were estimated for the soft panel samples and compared to the NIJ-C3 and NIJ-C4 test templates [6].

First, the width, or dimension A, of the soft panels were compared. Since the test templates specified in the standard do not include side overlap, but the manufactured samples do, to ensure that both sizes are graphically comparable, it is assumed that the minimum expected side overlap of 5.08 cm was used and distributed symmetrically on the front and back soft panels (see Figure 4).

The vertical axis indicates the widths of the soft panel pairs (front and back) without side coverage. The minimal and maximal limits of the NIJ-C3 and NIJ-C4 test templates widths are marked in orange.

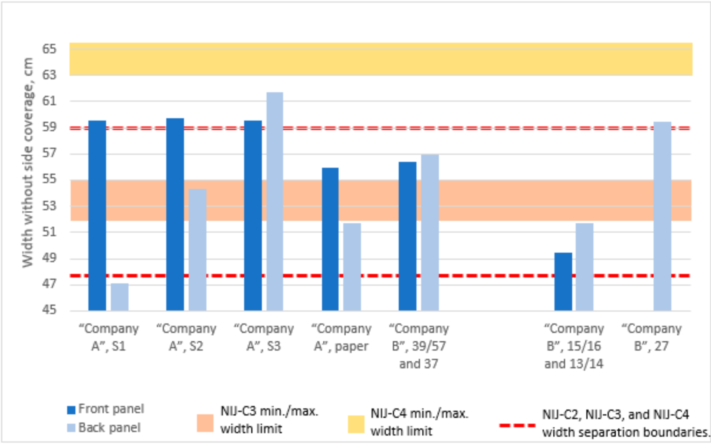

Figure 4. Width comparison of soft panel samples with corresponding NIJ standard test templates.

The graphic in Figure 4 clearly illustrates that the majority of the soft panels in width A correspond to the relevant test template. The widths of the outer garment BPV soft panels on the left slightly exceed the maximum width limit of the NIJ-C3 test template: the front panel by 0.3 to 0.7 cm, and the back panel by 2.35 cm for the S3 size (Company A), yet the back panel of the S1 size (Company A) does not exceed the NIJ-C3 by 0.7 cm.

Determination of the Height B of Soft Panels

The NIJ GUIDE [5] specifies the required position of soft panels in relation to specified anthropometric points on the body (see Table 3). This demonstrates that the height B of the soft panel is proportionate to the length of the soldier's torso. For panels of the same size designed for users of different heights, the height B will differ.

Document [5] specifies that the front panel should extend from below the jugular notch to two to three finger-widths (4.45–6.67 cm) above the top of the belt when standing. The back panel should extend approximately 5.08 cm below the collar and 2.54 cm above the belt.

Figure 5 illustrates the height B dimensions of all investigated soft panels. It was determined that the studied undergarment BPV soft panels were designed for tall users with torso lengths above 50 cm, therefore, the height B of the back panels exceeds the maximum height B restrictions of the NIJ-C3 and NIJ-C4 templates. On the other hand, the height of the front panel B is less than the minimum height restriction of the NIJ-C3 test template, which can be explained by the allowable neckline recess of up to 5.54 cm.

The comparison of the outer garment BPV soft panels of both manufacturers, showed that their height B measurements did not reach the minimum specification limit of the corresponding NIJ-C3 test template height B. This could be because the BPV can be accompanied with shoulder and neck protectors to cover the sections of the body not protected by the BPV soft panels. Protectors overlap with the front and back soft panels. However, it should be noted that the shoulder and neck protectors are not always used.

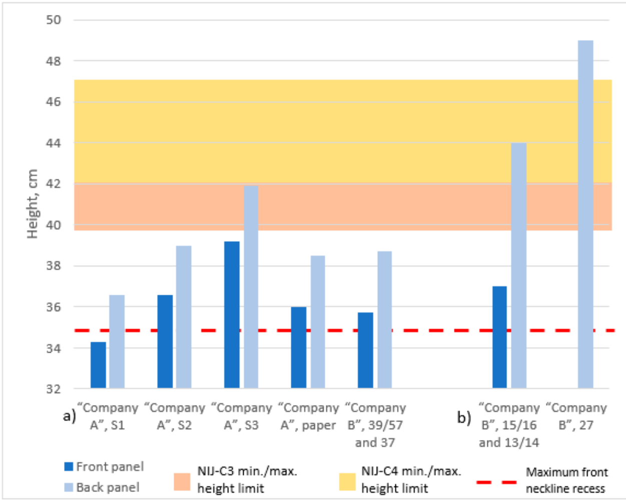

Figure 5. Height B comparison with the NIJ-C3 and NIJ-C4 test templates; a) outer garment, b) undergarment.

Determination of the Width C of the Soft Panels

The top width C of the analyzed outer garment BPV front soft panels mostly exceeds the maximum limit value of the NIJ-C3 test template, while the back panels are below the minimum limit value (see Figure 7) by 0.7 to 2.1 cm. Undergarment back panels no. 27 are 4.3 cm short of the NIJ-C4 template's minimum top width requirement.

The upper part width of the examined soft panel front parts has an obliquity (E) of 4.2 to 6.3 cm, which is significantly exceeds the maximum of 1.9 cm allowed by the NIJ test templates (see Figure 6). However, given that the C parameter of the studied soft panel samples mostly exceeds the maximum limit of the NIJ-C3 test template, the larger obliquity helps bringing the mid-width of the top ($C_{average}$) closer to the standard. This can be explained by the intention to reduce the area of the soft panels, and thus increase the protection in the armpit area.

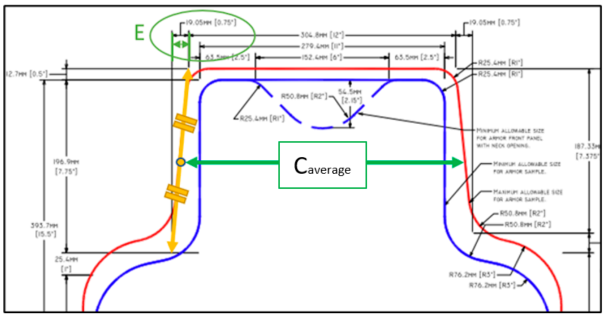

Figure 6. Allowed obliquity (E) of the soft panel upper part width (C) of NIJ test templates [6].

Even though measurement C of panel no. 27 should be within the NIJ-C4 test template's limits, the upper part width of the undergarment BPV soft panels does not even satisfy the NIJ-C3 test template's minimal limit. The upper part width of this panel is narrowed by 1.5–4.2 cm compared to dimension C of the NIJ-C3 test template.

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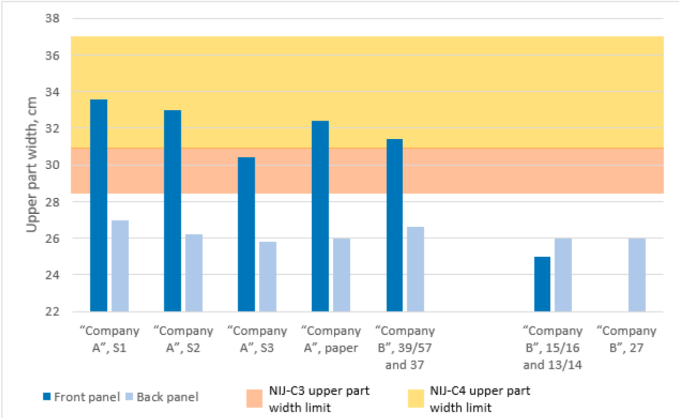

Figure 7. Upper part width (C) comparison with the NIJ-C3 and NIJ-C4 test template limits.

Determining the Configuration of Soft Panels

By matching the contours of the front and back undergarment BPV soft panels of the "Company B" with the corresponding NIJ-C3 test template (see Figure 8 with blue contour), the overall dimensions and configuration of the soft panels are compared to the NIJ standard test template.

As the soft panel height B is increased to fit tall user with torso length > 50 cm [19], it causes an increase in the total surface area. In order to keep the soft panels fit in the specific area of the NIJ-C3 test template, the upper corners of the back panel have obliquity.

Looking at the configuration of the undergarment BPV soft panels relative to the configuration of the corresponding NIJ test template, it can be seen that the bottom edge of the soft panels is curved to provide a snug fit. The size of the curve depends on the difference between the chest and waist circumferences of the soldier figure, as well as the tolerances in those circumferences.

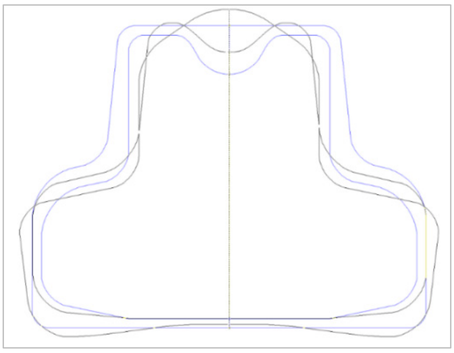

Figure 8. Comparison of "Company B" LL size undergarment BPV soft panels (black line) with the NIJ-C3 test template configuration (blue lines).

Output Parameters for Designing Soft Panels

The NATO standard STANAG requires each member state to produce as small range of sizes as possible, covering national demand [7]. At the local military apparel production Company A, it was discovered that the regional type figure length ranges from 160 to 200 cm, with a chest circumference of 80 to 140 cm.

To ensure the modularity and comparability of BPV in all NATO member states, the STANAG 2335 standard defines a graduation step by length and circumference group sizes of 5, 10, and 15 cm (the step must be divided by 5), as well as a size marking code consisting of 8 symbols, where the first four numbers indicate length graduation and the next four indicate chest circumference graduation [7].

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The designed soft panels will be graded for three different body heights: short (168 cm), regular (182 cm), and long (196 cm). Figure 9 illustrates the full-size coverage. The numerical names of the sizes correspond to the codes established in the STANAG 2335 standard, while the letter designations provide easier comparison at the national level.

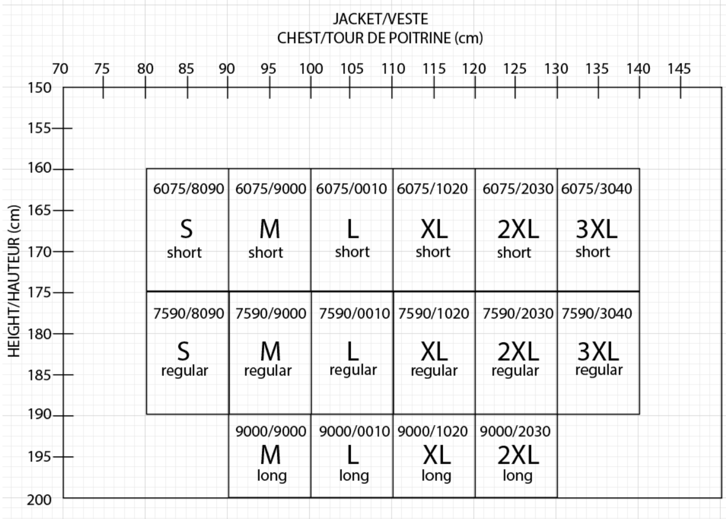

Figure 9. National BPV size coverage.

It was challenging to obtain the current body measurements in the specific region because all the available measurement tables were outdated and companies were reluctant to share their accumulated measurement systems. Developing a table of measurements for the target audience by taking measurements and compiling them is a time-consuming process that would require separate research. All previously published literature sources of measurements were combined into one chart and sent to Company A to update basing on the current situation. Resulting in a table of measurements required for all 16 sizes with the gradation specified in the STANAG 2335 standard.

To estimate the needed tolerances for chest and waist circumferences, a mannequin was fitted with layers of army clothing, and the increase in circumferences at the chest and waist levels was observed. Outer garment BPV is worn over the layers of garments shown in Figure 10. The thickness of six layers, which is worn under the BPV, has raised the chest circumference by 10 cm and the waist circumference by 7 cm. The average tolerances for outer garment BPV were 5.8 cm at the chest and 3.7 cm at the waist.

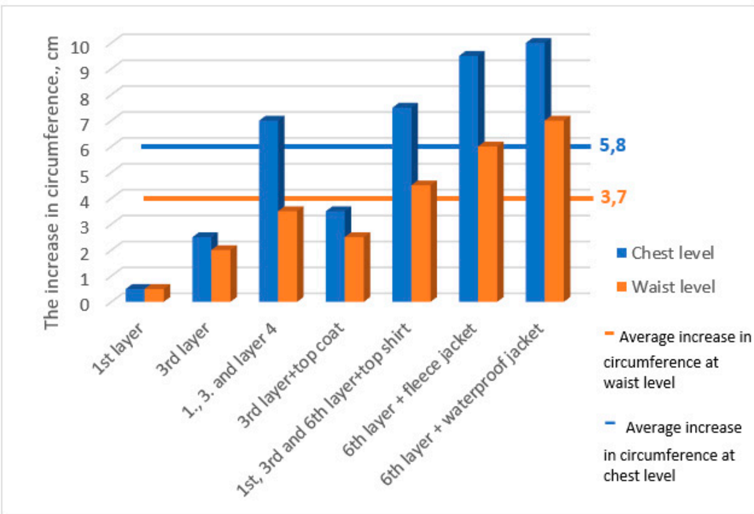

Figure 10. An increase in the circumference of layers of clothing worn under the outer garment BPV at chest and waist level.

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Undergarment BPV is typically worn on the first layer of clothes (1 or 2 undershirts), allowing BPV to be created with smaller tolerances (see Table 5). On the other hand, numerous layers of clothing worn under the outer garment BPV and possibly even the undergarment BPV, result in higher tolerances and directly affect the surface area and configuration of the soft panels.

Table 5. Tolerances for undergarment and outer garment BPV.

Designation	Name	Tolerance size for undergarment BPV, cm	Tolerance size for outer garment BPV, cm
V_{kra}	Tolerance in chest circumference	4	7
V_{va}	Tolerance in waist circumference	2	4
V_{mgpl}	Tolerance for back width	1	1.75
V_{krpl}	Tolerance for front width	0.5	8.8
V_{rocei}	Tolerance in armpit area	2.5	4.37

Designing Soft Panels

During the development of the soft panels, the first challenges arose and contradictions in the standards were revealed. For example, the NIJ standard states that the soft panel should cover the largest possible body area to obtain the maximum absorption of ballistic energy. When designing the first version exactly according to the maximum characteristics of each size of the proposed NIJ standard test templates and determining the area of each designed soft panel, it was discovered that the area of the M regular size for the back panel, used for comparison, was bigger (0.1841 m2) than the investigated "Company 2" no.13 and no.14 soft panel samples of comparable size (0.1639 m^2). Furthermore, the upper part width C is at its maximum limit (indicated with a red circle in Figure 11) according to the standard LVS EN 13921:2007 ergonomics criteria [20]. This causes the discomfort to stretch the arms forward. The contradictions that emerged during the creation of Version 1 indicate that an unreasonable increase in the surface area of soft panels reduces physical comfort and interferes with mobility, as the increased surface area limits movements. Additionally, this approach requires more fabric, making the soft panels and BPV heavier. The green circle line in Figure 11 illustrates a corner that can be rounded to a bigger diameter to minimize area, as the front panel overlaps the back panel at this location.

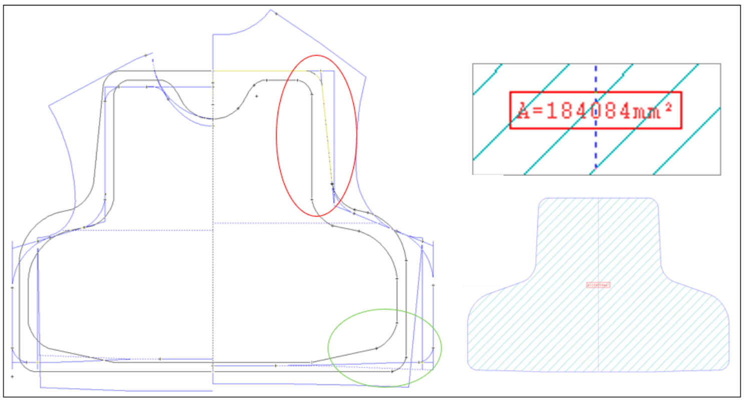

Figure 11. Version 1 for the back panel of M regular size (developed in CAD Grafis)**.**

All of the issues mentioned above were solved in the next version of soft panel development. To ensure that the back panel was not noticeably larger than the front panel in the second version within the BPV of the same size, the top corner obliquity was designed for the back panel (Figure 12 with the red circle line), and the front panel was given 90% of the side overlay size. In this version, the area of the back soft panel of M regular size was 0.1498 m^2, which is less than the 0.1639 m^2 of the studied sample no. 14 and significantly less than the area of the pattern in Version 1.

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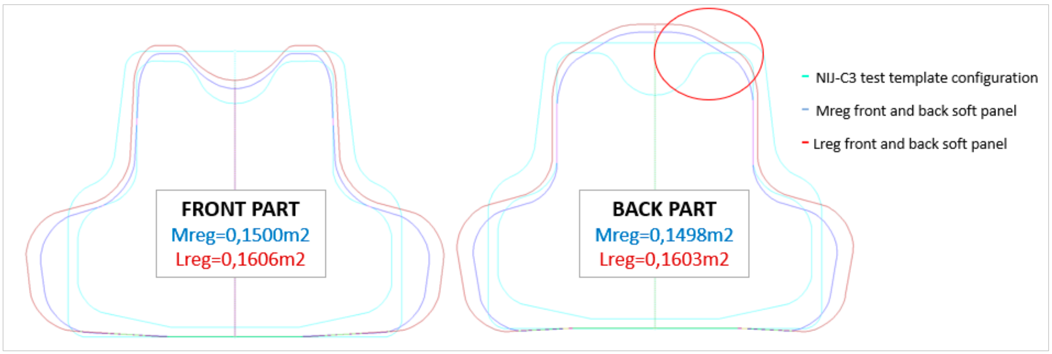

Figure 12. Version 2 comparison between M and L regular size soft panels with the corresponding NIJ-C3 test template [6] (developed in CAD Grafis).

However, when sizing Version 2, it was difficult to satisfy the national demand (for the height range of 160–200 cm and a chest circumference of 80–140 cm). When grading the back panels on shorter soldier figures and compared to the NIJ standard test templates [6], the obliquity corners significantly reduced shoulder coverage (5-7 cm), thus, reducing ballistic protection.

The first two versions of the soft panels were designed to fit seven sizes, ranging from XS to XXXL, ignoring soldier height differences within one size. This option satisfies the STANAG standard requirement [7] to cover the demand for the smallest sizes only at the national demand, making the BPV more convenient for manufacture and assembly between NATO alliance countries. However, when grading and measuring against the specific soldier figure, it was determined that this type of gradation does not completely cover all demands, reduces ballistic protection for taller members due to shortened BPV torso proportions, and unnecessarily increases surface area and weight for shorter users, reducing their comfort, mobility, and overall ballistic protection.

Next, the third version of the soft panel design was created on the 16 sizes shown in Figure 9, with 6 short sizes from S-3XL designed for shorter soldiers from 160–175 cm in height, the next 6 regular sizes for heights between 175 and 190 cm, and 4 additional sizes for tall users over 190 cm in body height. Figure 13 illustrates the configuration of version 3 and the M regular size surface areas for the front and back panels.

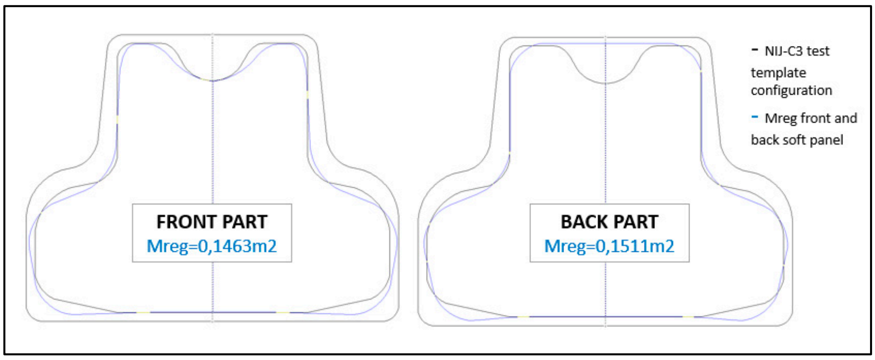

Figure 13. Comparison of Version 3 M regular-sized soft panels with the equivalent NIJ-C3 test template [6] (developed in CAD Grafis).

The third version's M regular size was measured on a mannequin that matched the soldier figure's chest circumference of 100 cm and waist circumference of 86 cm. The fitting indicated that the side overlay should be designed symmetrically for the front and back panels. When adding 90% of the overlay to the front panel, the BPV closure moves to the back, making it more difficult to close, open, and adjust. However, in general, the soft panel design was adequate for the corresponding NIJ test template (see Figure 14), and fitting in the CAD program Clo3D virtual environment for sizes S–XL in short, regular, and long variations could be performed.

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Figure 14. Fitting M regular soft panels on an appropriately sized mannequin.

When preparing the soft panels of different sizes for virtual fitting, the side line displacement of the front and back panels that did not appear in the actual fitting was discovered (see Figure 15 with the orange circle line). The analysis showed that this displacement had occurred due to the different starting points of the soft panels above the work belt, which ranged from 4.45–6.77 cm in the front to only 2.54 cm in the back and were not aligned in the side seam. The same displacement of sideline was also obvious in the Clo3D fitting (see Figure 16), and it was fixed in the final version which is illustrated in Figure 15.

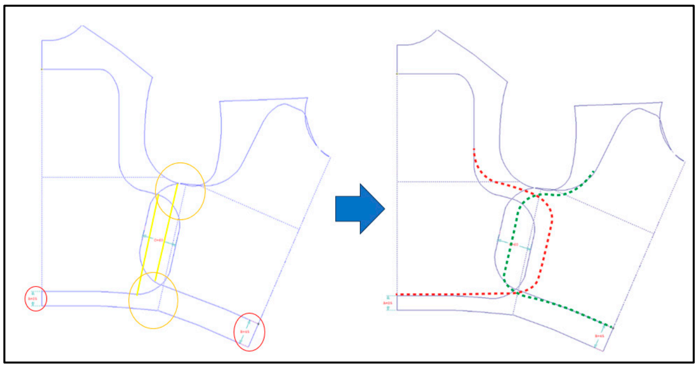

Figure 15. Displacement of the front and back soft panels in the sideline for the M regular size (developed in CAD Grafis).

Figure 16. M regular size virtual fitting in the Clo3D program.

The outer garment soft panels were designed based on the undergarment soft panel patterns, with changed tolerances. The top of the front panel straightened towards the junglar notch, and coverage increased in the armpit and chest areas. However, when sewing and placing the BPV with inserted soft panels and hard plates on the appropriate size mannequin, a new defect was revealed. Because of the hard plate that did not match the body curves identically and gave free space between the BPV and waist, the BPV was too small for the relevant size, unable to form the minimum 5.08 cm side overlay (see Figure 17). Detailed analysis indicated that, the hard plate and the layers of clothes worn underneath significantly increase the volume at the waist level. Therefore, when designing the outer garment BPV soft panels the chest circumference needs to be equal to the waist circumference.

Figure 17. Outer garment BPV's first fitting for size M regular.

In the result, the undergarment and outer garment BPV soft panels in all necessary sizes were designed by addressing the previously mentioned issues, adhering to the NIJ standards [4,6], GUIDE [5] and a thorough literature analysis [19–21,23]. Additionally, the studied dimensions and configurations of existing BPV soft panel examples were considered. This approach ensures that the BPV meets national requirements while remaining adaptable to the individual body types of soldiers, thus fulfilling the research's purpose.

The soft panels were designed for three different body heights—short, regular, and long—providing optimal ballistic protection coverage without adding unnecessary weight to users of the same size but different body heights. Figure 18 illustrates the complications that arise when this height gradation is not performed. The figure indicates, in green, that an average body height of approximately 180 cm is suitable, but shorter and taller users will encounter issues.

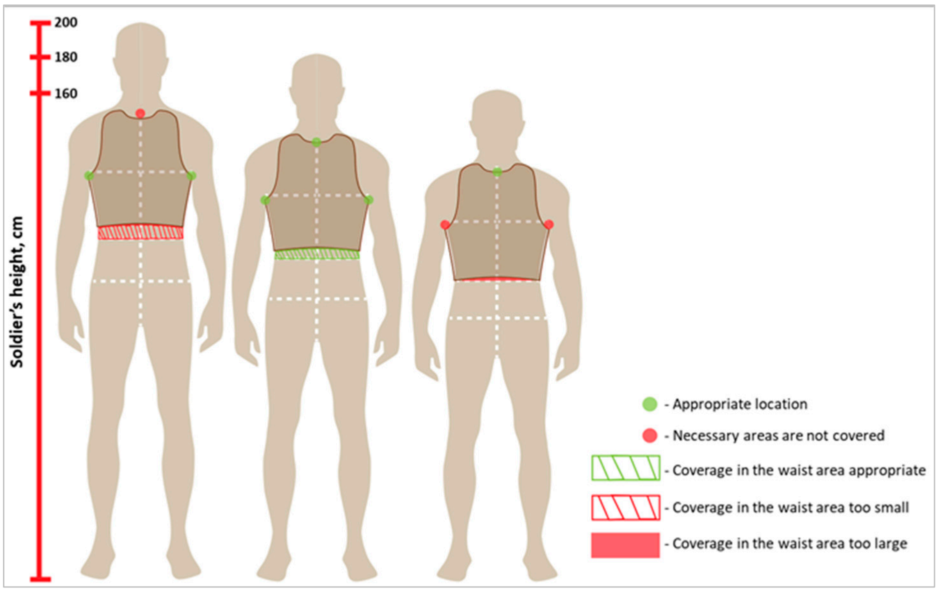

Figure 18. Soft panel problems (marked red) if the height gradation is not performed.

The research concluded that the GUIDE [5] provided more detailed instructions for designing soft panels in relation to the proportions and specific points of the human body, particularly regarding the A and B dimensions. However, the NIJ standard [4,6] test templates serve as a useful starting point for manufacturers and researchers who are new to this field. These templates help in verifying whether, for example, a designed soft panel provides adequate ballistic coverage in the chest area for a specific size (dimensions C and D).

Although the configuration analysis of the available soft panel samples indicated differences from the NIJ standard test templates, it was evident that manufacturers attempted to comply with the standards by modifying them to fit the intended size and body shape. While NIJ standard 0101.06

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strictly defines the surface area limits for soft panels of various sizes and the exact configuration of the corresponding test templates, it does not specify which specific standardized soft panel test template surface area corresponds to each BPV type (outer garment or undergarment) and size.

This raised questions and confusion about how to match a designed BPV size to a specific NIJ test template for testing and usage dimensions. Constructing one version, measuring the surface area, then making modifications and constructing additional versions is a time-consuming and unpredictable process, as modifying the parameters affects the surface area of the new soft panel, necessitating a restart of the process.

Since dimensions A (panel height) and B (panel width) are closely related to the height and chest circumference of the body, and the minimum side overlay of 5.08 cm is known, the research discovered a method for calculating the surface area of the designated soft panel before it is created. By multiplying the known parameters A and B, the surface area for a rectangle is obtained, but not for the soft panel itself. To obtain the needed surface area, these dimensions A and B should be multiplied by the coefficient K, which accounts for all curves of the soft panel (see Figure 19). As the back and front panels have different curves, the coefficients values differ for these panels, depending on the type of BPV.

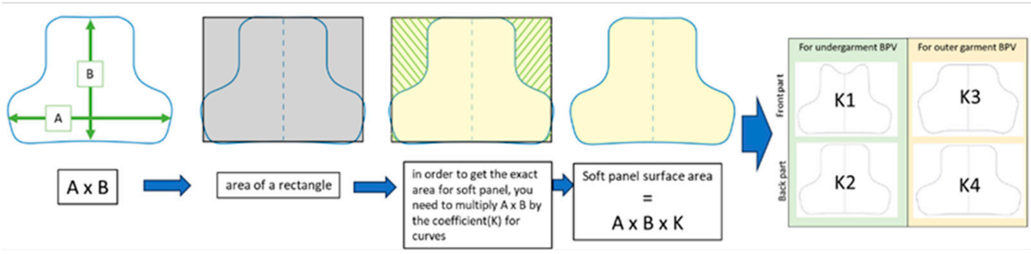

Figure 19. Obtaining the coefficient K for the calculation of the surface area of the designed soft panels.

The coefficient magnitude was determined based on the overall dimensions of the NIJ 0101.06 standard test templates [6], with the minimum and maximum coefficients being within the range of 0.7–0.84. Figure 20 illustrates an example of calculating coefficient limits for the NIJ-C3 test template.

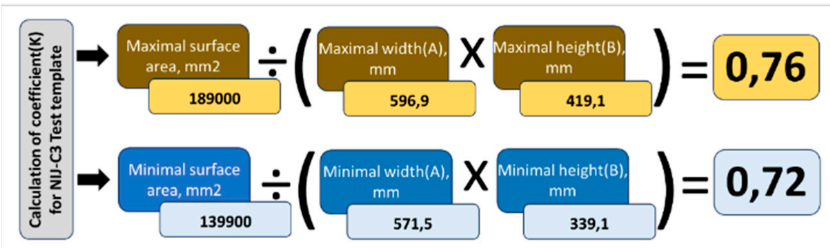

Figure 20. Calculation of the coefficient K for the NIJ-C3 test template.

These coefficients were then verified on the soft panels created for the research. By using a coefficient of 0.78 for the front panels and 0.7 for the back panels, a comparison of the calculated and actual surface areas for the undergarment BPV soft panels revealed a potential error of 4.7%, 3.9% for the outer garment, with an average error of 4.3%. This suggests that the calculated coefficients and surface area calculation formula for soft panels are sufficiently accurate for research purposes.

Knowing the affiliation of each planned size to a specific NIJ standard test template allows us to verify that we are proceeding in the correct direction and to understand the origins of the C and D dimensions for soft panels. The design process for the soft panels started with the creation of the basic block pattern, developed in the CAD GRAFIS program using the SEPP unified construction approach. A regular size M, corresponding to a chest circumference of 96 cm, was used as the basic size for the construction. The tolerance sizes used for the undergarment and outer garment BPV are indicated in Table 5.

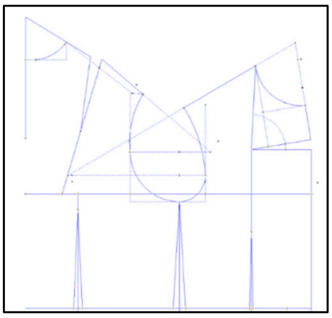

Figure 21. Basic block pattern of M regular size BPV (developed in CAD Grafis).

The A and B soft panel characteristics are obtained from the GUIDE [5] and are closely related to the soldier's body height and chest circumference, while the upper part width (C) and upper part height (D) measures are calculated from the corresponding NIJ standard test templates, providing optimal protection in the chest and armpit area. There will be several soft panel sizes to be designed within one NIJ test template. To ensure equal gradation, the maximum number of sizes from the same length for one test template (n_{max}) should be determined, which in this case is four (n_{max} = 4). The measurement range is obtained by subtracting the test template's maximum ($T_{nmax}C_{max}$) from its minimum ($T_{nmax}C_{min}$) (see Table 6), which, when divided by n_{max} - 1, yields the size gradation step. Below is an example (2) and the entire formula (1) for calculating the upper part width for sizes M-2XL regular that belong to the NIJ-C3 test template:

$$(TnmaxCmax - TnmaxCmin)/(nmax -1) \quad (1)$$

$$(304.8 – 279.4)/(4 - 1) = 8.47 \text{ mm (step for upper part width (C))} \quad (2)$$

For the smallest of the sizes – M regular, the width of the top is 279.4 mm, L regular, and for each subsequent size, a step of 8.47 mm is added.

Table 6. Summary for the NIJ standard test template [6] dimensions.

Main characteristics of the NIJ Test templates								
	Width(A), mm		Height(B), mm		Upper part width(C), mm		Back upper part height, mm	Front upper part height, mm
Template	A_{min}	A_{max}	B_{min}	B_{max}	C_{min}	C_{max}	D_{back}	D_{front}
NIJ-C1	292.2	317.5	292.1	317.5	228.6	254	146.1	136.5
NIJ-C2	406.4	431.8	342.9	368.3	254	279.4	171.5	161.9
NIJ-C3	520.7	546.1	393.7	419.1	279.4	304.8	196.9	187.3
NIJ-C4	635	660.4	444.5	469.9	304.8	330.2	222.3	212.7
NIJ-C5	749.3	774.7	495.3	520.7	330.2	355.6	247.7	238.1

In the study, the process of designing undergarment and outer garment BPV soft panels was transferred in the algorithm, illustrated in Figure 22.

The algorithm for designing soft panels begins with the preparation of initial data, which includes the necessary size coverage, graduation steps, and accurate body measurements for constructing the basic block pattern.

The basic block pattern is then created and prepared for soft panel modeling by closing the chest, waist, and shoulder darts for both the front and back parts. This completes the preparation process and enables the establishment of the main characteristics of the soft panels.

The first step is to mark the starting points of the upper and lower edges of the soft panel along the center line of the front and back. These distances, defined in Table 2, form parameter B. The next step is to determine if armhole lowering is necessary, which depends on the type of BPV (undergarment or outer garment) and the desired level of armpit coverage. According to the NIJ standard [6] and related documents [5], the soft panel should be as close to the armpit as possible.

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Based on measurements obtained during the research, the recommended distance for undergarment BPVs is 1-2 cm, while for outer garment BPVs it is 0-1 cm.

The width of the soft panel (A) is then determined by the width of the basic block pattern, to which a minimum of 5.08 cm of side overlay is added on each side. The size of the overlay can be divided equally between the back and front panels or adjusted as needed.

The height and width of the upper part are adjusted based on the calculated sizes from the NIJ test template (see Table 6). The final steps involve connecting points with lines and designing the corners to complete the soft panel shape.

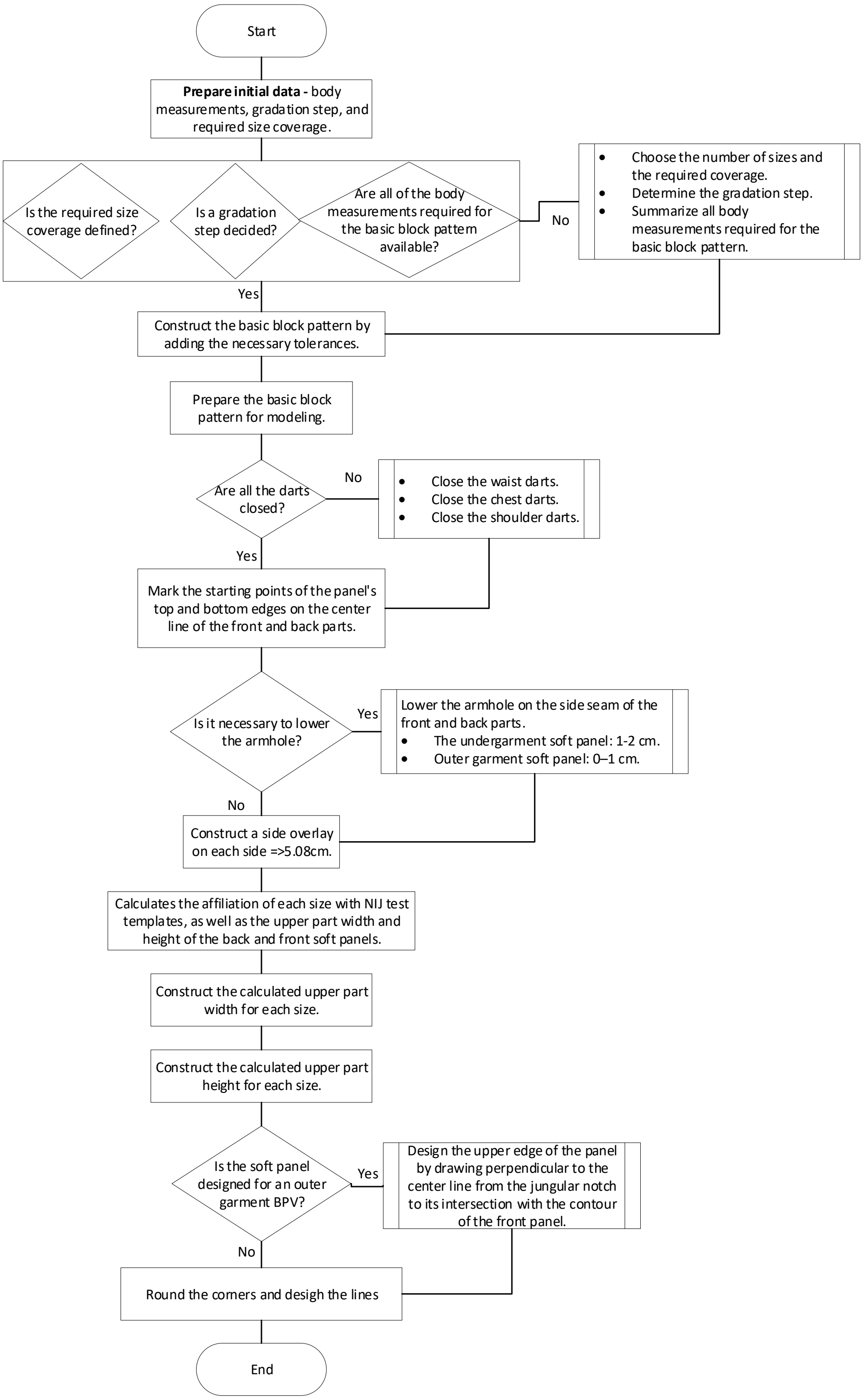

Figure 22. Soft panel design algorithm.

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4. Conclusions

This research contributes to the field of ballistic protection by offering a standardized approach to designing soft panels for BPVs. By addressing the specific body type requirements of regional soldiers and adhering to relevant standards, the study enhances the modularity and adaptability of BPVs. Future research should focus on further refining the algorithm and exploring its application across different regions and standards.

In this research, we developed undergarment and outer garment BPV soft panel patterns in 16 sizes to cover the entire national soldier population. These patterns were designed based on the national army soldier body measurements, enhancing the comfort and adaptability of BPVs to the body types of the target audience. By using these soft panels, we aim to improve the modularity of BPVs in line with modern PPE requirements while ensuring maximum comfort and size adaptability for various figures. The methodology developed in this research can also assist other regions in designing BPV sizes tailored to their specific body types.

The coefficient (K) size is a critical aspect of this research as it allows for the calculation of the surface area of the designed soft panel before construction. This saves time by eliminating the need to construct the panel, measure the area, make adjustments, and restart the process. This coefficient enables easy comparison with NIJ test templates and facilitates further calculations for material consumption or the total weight of the soft panel.

In the next stage of the project, we will develop a modern BPV construction based on the designed soft panel patterns, enhancing its modularity to meet NIJ standards [6] and accompanying document [5] recommendations. We will also consider the current requirements of local army soldiers for more convenient use of BPVs, thereby improving their performance in daily tasks.

The numerous demands from soldiers for BPV improvements highlight the need for enhanced BPV modularity in the specific region. Improved modularity will allow BPVs to be assembled to fit different body types and perform various tasks while providing the necessary level of ballistic protection as specified by NIJ standards.

Future research should focus on refining the algorithm and testing it with a broader range of body types and different regional specifications. Further analysis of new materials and their impact on the design and comfort of BPVs will also be beneficial.

Author Contributions: Conceptualization, D.B., I.Z., V.M.; methodology, D.B., D.A.; validation, D.B., M.G. and I.Z.; formal analysis, D.B., I.Z.; investigation, D.B., M.G.; resources, D.B., M.G.; data curation, D.B., M.G.,I.Z., D.A.; writing—original draft preparation, D.B.; writing—review and editing, D.A., I.Z., M.G., V.M.; visualization, D.B., M.G.; supervision, I.Z., D.A.. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Ministry of Defence Republic of Latvia project "Graphene-and-silica-aerogel-enhanced lightweight ballistic protection vest prototype with integrated pressure-sensitive layer for multi-zone impact detection", project No. VPP-AIPP-2021/1-0009" and Riga Technical University funding for project "Modular ballistic protection vest", project No.0400-1.3-e/23 l ZM-2023/22 l 4823.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Precedence Research. Available online: https://www.precedenceresearch.com/body-armor-market (accessed 01.2023).
2. MarkWide Research Inspiring Growth. Available online: https://markwideresearch.com/ballistic-protection-market/ (ac-cessed 01.2023).
3. Qian-ran Hu, Xing-yu Shen, Xin-ming Qian, Guang-yan Huang, Meng-qi Yuan. The personal protective equipment (PPE) based on individual combat: A systematic review and trend analysis. *Defence Technology* 2023, *Volume 28*, pages 195-221, ISSN 2214-9147, Available online: https://www.sciencedirect.com/science/article/pii/S2214914722002719.
4. Vigne, N.L. NATIONA INSTITUTE OF JUSTICE. Ballistic Resistance of Body Armor NIJ Standard 0101.07.

5. Holder, E.H.; Mason, K,V.; Sabol, V.J. NATIONAL INSTITUTE OF JUSTICE GUIDE - BODY ARMOR. Selection & Applica-tion Guide 0101.06 to Ballistic -Resistant Body Armor, 2014.
6. Mukasey, B.M.; Sedgwick, J.L.; Hagy, D.W. NATIONAL INSTITUTE OF JUSTICE. Ballistic Resistance of Body Armor NIJ Standard-0101.06.
7. STANAG 2335 - INTERCHANGEABILITY COMBAT CLOTHING SIZES.
8. Hard Shell. Available online: https://www.hardshell.ae/size-chart/ (accessed 2023)
9. Alvanon. Available online: https://alvanon.com/wp-content/uploads/2018/06/AF-SPECS_ASD-EU-Men_v4.0__06MAR2015.pdf (accessed 2023).
10. Safeguard Armor. Available online: https://www.safeguardarmor.com/pages/size-chart (accessed 2023).
11. Bullet Safe. Available online: https://bulletsafe.com/pages/bulletproof-vest-size-chart (accessed 2023).
12. BAO, Body Armor Outlet. Available online: https://www.bodyarmoroutlet.com/pages/sizing-charts (accessed 2023).
13. BAO, Body Armor Outlet. Available online: https://www.bodyarmoroutlet.com/products/baot-cxiiia-xseries-w-iiia-ballistics (accessed 2023).
14. Protection Group Danmark Wholesale ApS. Available online: https://protectiongroupdenmark.com/shop/4-bulletproof-vest/ (accessed 2023).
15. GH Armor. Available online: https://www.gharmor.com/sizing (accessed 2023).
16. National Body Armor, Concealed experts. Available online: https://nationalbodyarmor.com/pages/sizing-chart-1 (accessed 2023).
17. The Tactical Boutique. Available online: https://www.thetacticalboutique.com/product/bulletsafe-bulletproof-vest (ac-cessed 2023).
18. Safe Life Defence. Available online: https://safelifedefense.com/concealable-multi-threat-vest-level-iiia-hg2 ((accessed 2023).
19. Šitvjenkins, I. Karavīra individuālās aizsardzības sistēma. Lietošanas rokasgrāmata 2008 Volume 1, 160 pages.
20. NATO standard AEP-2333 "Combat clothing performance and protective properties and trial guidance".
21. LVS EN 13921:2007 - "Individuālie aizsarglīdzekļi. Ergonomiskie principi".
22. Vigne, N.L. NATIONA INSTITUTE OF JUSTICE. Specification for NIJ Ballistic Protection Levels and Associated Test Threats - NIJ Standard 0123.00.
23. Dabolina, I.; Lapkovska, E.; Vilumosone, A. Dynamic Anthropometry for Investigation of Body Movement Comfort in Protective Jackets. In Functional Textiles and Technology; Majumdar, A., Gupta, D., Gupta, S.; Springer Singapore: Singapore, 2019 pp. 241-259. https://doi.org/10.1007/978-981-13-7721-1_20