

# Body Armour Comfort & Mobility Assessment and Implementation

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**Abstract.** Comfort issues associated with body armour have become a crucial focus for military and law enforcement. As the demand for reliable personal protective equipment increases, the user comfort and mobility constraints induced by body armour have emerged as essential factors influencing wearability and performance. Despite advancements in material technology allowing weight reductions, many users experience discomfort due to rigidity and the restrictive nature of traditional body armour.

Comfort and mobility testing of body armour is thus a pivotal aspect of developing effective personal protective equipment, as it directly influences user acceptance and operational performance. Body armour, while designed primarily to offer protection, must also consider the physical and psychological impact on the wearer.

This paper discusses body armour comfort testing methods addressing issues identified during wear trials and considering feed-back from end-users. Aside from fitting issues, the most prominent discomforts and mobility constraints were related to either a high rigidity of the armour construction reducing mobility and accelerating exhaustion, or pains occurring at localized pressure areas. Three test methods were developed allowing to characterize these aspects. The fundamental consideration of the test method designs is to replicate in-use movements and anatomical aspects observed during wear and were shown to correlate well with user perception.

The test methods, first presented at PASS 2023, have been further optimized and are now available to the industry. They allow to include quantified comfort and mobility criteria in the design of ballistic protective materials and solutions. End-users, for whom comfort is most critical, can now use and eventually include comfort and mobility criteria in tender processes in parallel to ballistic protective performance, weight and cost. Ultimately, the target for these new additional selection criteria is to reduce the likelihood of fatigue and distraction in-use. Illustrations of the implementation of these test methods to the selection of soft ballistic inserts are presented in this paper.

## 1. INTRODUCTION

### 1.1 The stake around comfort & mobility assessment

The necessity for comfort in body armour is increasingly acknowledged by end-users who require protective equipment that does not compromise operational performance. Although ballistic efficacy—shaped by the materials and design of the body armour—exhibits a strong correlation with the level of protection provided, the importance of ergonomics must not be underestimated. Enhanced comfort alleviates painful movements and pressure points, thereby promoting more consistent and effective utilization of the vest. Furthermore, improvements in mobility can mitigate movement restrictions and facilitate energy conservation, leading to enhanced operational efficiency, decreased exposure to hazardous environments, and reduced risk of musculoskeletal injuries.

A thorough literature review conducted by Pope et al. [1] demonstrated that body armour substantially impacts physical performance and introduces biomechanical constraints for the wearer. However, they emphasized that the effects of body armour on marksmanship and physiological responses remain insufficiently explored. Their findings underscored the importance of deliberate consideration in body armour selection, factoring in ergonomic aspects alongside their implications for perceived and measured exertion, work capability, balance, and stability.

Recent field surveys [2] reveal that police officers often feel compelled to remove their body armour owing to discomfort, highlighting the detrimental effects that body armour can impart on user well-being and effectiveness. Even if heat has been recognized as a significant element influencing this behaviour, similar to the instinct to discard a sweater in warm conditions, almost 50% of respondents identified discomfort as the primary reason for removing their protective gear, whereas concerns related to weight were expressed by only about 25% of participants, indicating that comfort is paramount in the selection of body armour.

Moreover, research investigating military body armour indicates that diminished mobility may adversely impact movement, posture [3], and range of motion, [4] even when the equipment weights are relatively moderate. Thus, ergonomics, defined as the harmonious integration of comfort and mobility,

is expected to not only affect immediate performance outcomes but also potentially heighten the long-term risk of musculoskeletal disorders.

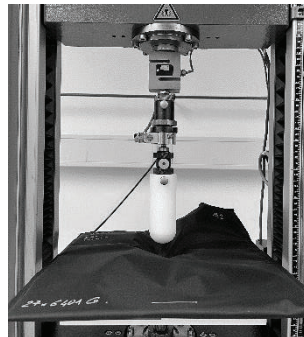
Despite recent advances in materials designed to enhance comfort without compromising ballistic protection, a consensus on clear and objective standardized testing methods remains elusive. As a result, assessing comfort presents a significant challenge for end-users during the body armour selection process, in conjunction with other critical factors such as ballistic performance, cost, and weight. The lack of established criteria for comfort further complicates the efforts made by manufacturers to develop solutions that prioritize user comfort.

## **1.2 Past assessments of comfort & mobility have been undertaken through a range of methodologies which have not resulted in fully satisfactory outcomes to date**

The assessment of comfort and mobility constraints in body armour through various methodologies—including weight measurement, plunger pressure tests, pole or table edge tests, and wear trials—reveals significant limitations that undermine their relevance in providing accurate evaluations.

### *1.2.1 Incumbent test methods*

Weight measurement alone is insufficient for a comprehensive understanding of comfort and mobility, as it fails to encapsulate the nuanced experiences of wearers. The plunger pressure test, while quantifying material resistance to complex folding, often does not correlate well with subjective comfort perceptions during wear trials, primarily resulting from the original test design focused on single-layered fabric conformability rather than complex multi-layered constructions found in body armour constructions [5][6]. Similarly, the pole or table edge test, which measures the angle of deformation, lacks applicability in real-world movements during which body armour experiences multi-axial deformations, rendering its findings less representative of practical wear scenarios [7].



**Figure 1.** Example of plunger pressure test set-up used in DuPont

### *1.2.2 Wear trials*

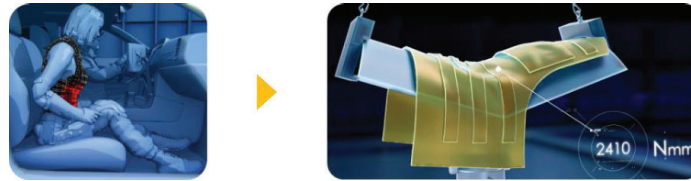
Although wear trials are considered the most realistic method for assessing comfort and mobility, these require significant resources and are not standardized across the different military and law enforcement agencies, complicating their implementation as benchmarks for body armour evaluation [8]. Collectively, these deficiencies indicate that current assessment methods inadequately address the multifaceted nature of comfort and mobility constraints experienced by end-users in actual operational contexts.

## **1.3 Three innovative Comfort and Mobility testing methods have been developed relying on real situations and body movement**

In response to the pressing need for enhancing the end-user experience for military and law enforcement personnel, three innovative laboratory test methodologies have been developed using a universal tensile testing machine (UTM). These testing methods address the main comfort aspects of mobility and constraints and are inspired by real-world operational scenarios and in such are designed to closely replicate the diverse range of dynamic body movements encountered by users in various environments. By allowing for the quantification of mobility constraints and comfort levels, these methodologies provide critical insights into the interactions between body armour and the wearer's physical capabilities.

### 1.3.1 The Lower Costal Bending (LCB) test

The first of these methodologies, known as the Lower Costal Bending (LCB) test, is specifically designed to simulate the bending motions of the upper body. During active duty, such bending movements are common, yet they often lead to significant energy dissipation and accelerated physiological fatigue among wearers. The LCB test serves an essential function by quantifying the resistance to bending and thus, the amount of energy lost due to the stiffness inherent in the ballistic solution. This quantification is critical for understanding how much energy the wearer expends during routine movements, thereby informing improvements in ballistic vest design for enhanced operational endurance. The recently published “HO-DPT 67474-2” test method procedure defines the energy,  $E_n.LCB$  expressed in N.mm, required to flex a soft ballistic insert at the lower costal bending axis of the torso.



**Figure 2.** Mobility constraints that led to the LCB test design

### 1.3.2 The Double Curvature Compression (DCC) test

In terms of mobility optimization, it is imperative that ballistic solutions conform effectively to the contours and shapes of the wearer’s body in authentic end-use situations. Observational studies utilizing advanced digital imaging techniques [9] reveal that body armour is frequently required to adapt dynamically to multi-curved shapes dictated by the human form. The Double Curvature Compression (DCC) test was established to replicate the anatomy of a bent torso, enabling value chain players to evaluate the conformability of various ballistic material solutions comprehensively. A high degree of conformability is intrinsically linked to enhanced mobility. The “HO-DPT 67474-3” test method procedure defines the energy required,  $E_n.DCC$  expressed in N.mm, to conform a soft ballistic insert to the anatomical multi-curved bent torso shape.



**Figure 3.** Mobility constraints that led to the DCC test design

### 1.3.3 The Edge Pressure (EP) test

Finally, the edges of the ballistic vests can contribute to localized discomfort and pains, particularly at critical pressure points such as the lower abdomen, neck, and arms. To address this issue, the Edge Pressure (EP) test has been developed. This test simulates the anatomical shape of the arm and the corresponding curvature of ballistic solutions to assess the discomfort generated at these potential pressure points. By identifying the causes of localized discomfort through the EP test, manufacturers can make informed design modifications to improve the overall comfort and functionality of body armour. The “HO-DPT 67474-1” test method procedure defines the force,  $F.EP$  expressed in N, developed at the edges of a soft ballistic insert during a given displacement.



**Figure 4.** Edge pressure pain that led to the EP test design

In summary, the collective implementation of these methodologies—namely, the Lower Costal Bending test, the Double Curvature Compression test, and the Edge Pressure test aims at proposing a comprehensive understanding of the intricate relationship between body armour and the limitations imposed on wearers' mobility and comfort. Through these advancements, the ability to identify and mitigate discomfort levels significantly contributes to fostering an improved end-user experience, ultimately enhancing the performance and well-being of those who rely on such critical protective gear.

## **2. APPROACH TAKEN**

### **2.1 Objectives**

The aim of this study is to present a methodology to implement and use these new test methods for each stakeholder, including end-users, ballistic armour manufacturers, and fabric weavers.

### **2.2 Principle**

In the ongoing effort to define the most relevant way to implement these testing methodologies in the industry, an extensive series of investigated exchanges have been conducted with key stakeholders within the ballistic armour value chain to define a specific use framework for each player.

#### *2.2.1 End-users focus*

The engagement with end-users allowed to articulate their specific requirements and preferences. Consequently, the identification of optimal strategies for integrating the proposed testing methodologies into tender documents has been defined, ensuring that the solutions were tailored to meet their distinct needs.

#### *2.2.2 Ballistic Armour Manufacturer focus*

Simultaneously, ballistic armour manufacturers have been approached, focusing on the assessment and comparison of under-development body armour solutions. Through this collaborative approach, manufacturers were able to gain a deeper understanding of how these testing solutions could be incorporated into the design processes. Key considerations during these discussions included the ballistic performance of the solution design, its flexibility capabilities, its overall weight, and the associated costs as main design criteria for a new body armour solution.

#### *2.2.3 Material provider focus*

Interactions with material providers such as fibres manufacturers or weavers, highlighted the application of these testing methodologies in the development of innovative and flexible structural designs. This allowed for informed decision-making regarding the selection of raw materials that would most significantly enhance the desired properties of final ballistic products.

This multifaceted approach not only underscores the collaborative nature of innovation in the field of ballistic armour but also emphasizes the importance of stakeholder engagement in defining and implementing standardized testing solutions that align with the needs of the industry.

## **3. EXPERIMENT**

### **3.1 End-User experiment**

To evaluate the effectiveness of end-user solutions, a dedicated testing campaign was conducted to assess four distinct solutions designed to meet the requirements of level IIIa ballistic protection, specifically through rigorous testing methodologies, including the Edge Pressure (EP) test and the Double Curvature Compression (DCC) test.

The primary objective of this assessment was to determine whether these solutions could be clearly differentiated based on their performance metrics. Furthermore, the study aimed to establish a scoring framework that would be suitable for use in a procurement tender process, ensuring that each solution could be objectively evaluated based on a standardized methodology.

### 3.2 Ballistic Armour Manufacturer experiment

In the context of a comprehensive evaluation conducted for ballistic armour manufacturers, a total of eight distinct solutions were rigorously assessed based on varying levels of ballistic performance. Each solution was systematically organized within a comparative table, which delineated key parameters, including ballistic performance levels, flexibility scores, weight, and pricing.

The primary objectives of this assessment were twofold: first, to ascertain whether a strong quantifiable relationship can be highlighted between the degree of flexibility in the armour solutions and their corresponding ballistic performance; and second, to identify the optimal design according to the diverse evaluation criteria. To achieve these objectives, an analysis method was employed to investigate the potential trade-offs and synergies between flexibility and ballistic resistance.

### 3.3 Material provider experiment

In the context of material development, four distinct solutions were formulated, all featuring identical construction parameters and a consistent range of ballistic performance levels. Each of these solutions utilized a unidirectional configuration, while varying the product manufacturing process parameters and type of resin employed in their composition.

The primary objective of this study was to evaluate the flexibility of these solutions using the Double Curvature Compression (DCC) test, with the aim of identifying any perceptible differences among them. Additionally, the analysis sought to determine whether these observed differences in performance were significant enough to inform the selection of the optimal resin based on its flexibility characteristics.

## 4. RESULTS & DISCUSSION

### 4.1 End-User results

A series of intensive exchanges conducted with end users have culminated in the identification of two examples of viable options to be incorporated within the framework of a tender.

#### 4.1.1 Development of a Comparative Rating System

The first option involves establishing a systematic comparative rating mechanism. This approach would enable the positioning of body armour solutions based on their performance metrics, specifically aiming to minimize En.DCC or En.LCB, (measured in N.mm) and F.EP (measured in N) values.

The solution exhibiting the lowest Energy (En.DCC or En.LCB) combined with the lowest Force (F.EP) values would be awarded the highest number of points within this rating system, while all other body armour solutions would receive prorated scores accordingly. In the below example, the DCC test score of solution A is calculated by dividing its measured energy (En.DCC) by the energy measured for the sample with the highest En.DCC, sample D in this case,  $4'207 / 2'027=2.21$ .

This metric-driven evaluation strategy aims to facilitate objective comparison among different products in the tender submissions.

Solution	Ballistic level (NIJ)	En.DCC (N.mm)	DCC test score	F.EP (N)	EP test score	Flexibility score	Flexibility rating
A	Level IIIa	2'027	2.21	49	2.33	4.5	Highest flexibility
B	Level IIIa	2'825	1.58	85	1.34	2.9	2nd highest flexibility
C	Level IIIa	4'313	1.04	99	1.15	2.2	3rd highest flexibility
D	Level IIIa	4'473	1.00	114	1.00	2.0	4th highest flexibility

**Figure 5.** Comparative Rating System table

#### 4.1.2 Establishment of a Reference Point for Improvement

The second option proposes defining a benchmark using for example the currently deployed ballistic vest as a reference point. In this context, a scale of improvement, which may be expressed as a percentage, would be established in relation to this reference point.

The DCC test score and EP test score below would thus represent respectively the reduction in mobility constraint and the reduction of edge pressure versus a selected reference such as the system currently in-use.

This approach allows for a more nuanced assessment of the enhancements provided by new body armour solutions relative to existing standards, thereby enabling end users to gauge potential advancements versus a familiar system more effectively allowing end-users to select an improved solution with respect to incumbent in-use equipment.

Solution	Ballistic level (NIJ)	En.DCC (N.mm)	DCC (reduction of mobility constraint % Vs referenced solution)	F.EP (N)	EP (reduction of edge pressure % Vs referenced solution)	Reduction of edge pressure & mobility constraint (%) Vs referenced solution	Flexibility rating
A	Level IIIa	2'027	53%	49	51%	52%	
B	Level IIIa	2'825	35%	85	14%	24%	
C	Level IIIa	4'313	0%	99	0%	0%	Referenced solution
D	Level IIIa	4'473	-4%	114	-15%	-9%	

Figure 6. Comparative Rating System with a referenced solution

#### 4.1.3 In summary

Both options outlined above can be integrated into the tender process. By implementing these systematic approaches, stakeholders can facilitate a more informed and structured evaluation of body armour solutions, ultimately aiding in the decision-making process for procurement.

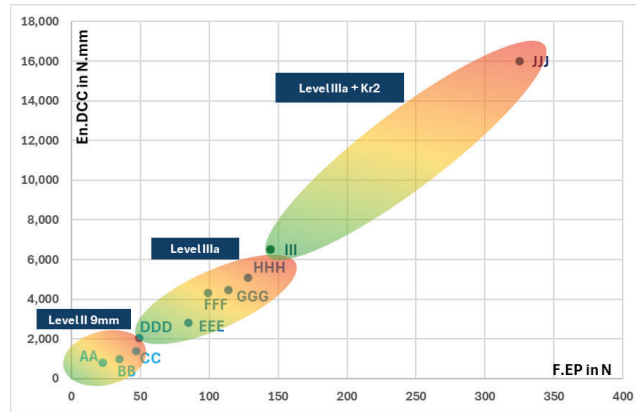
#### 4.2 Body Armour Manufacturer results

In the frame of this study, a total of ten viable solutions have been developed for body armour manufacturers and evaluated against various criteria, including the protection level, edge pressure, conformability, resistance to bending, weight, and price (Figure 7.).

As may be expected the protection level significantly influences the results of assessments related to the edge pressure, double curvature compression, and lower costal bending tests (Figure 8.). Following the test procedure recommendations, for En.DCC and En.LCB the values of the third sample solicitation are used. It is worthy to be noted that the comfort criteria and ratings are not in accordance with the respective solutions weights outlining the value of not only considering weights with respect to comfort characteristics.

Solution	Protection level	Comfort & mobility				Weight	Price
		Edge Pressure	Conformability	Bending stiffness			
		F.EP_after cycle	En. DCC_3rd trial	En. LCB_3rd trial			
		N	N.mm	N.mm	kg/m2		
AA	Level II 9mm only	23	785	NC	3.9	122%	
BB	Level II 9mm only	35	982	NC	3.9	98%	
CC	Level II 9mm only	47	1'586	NC	4.5	57%	
DDD	Level IIIa	49	2'027	NC	6.1	52%	
EEE	Level IIIa	85	2'825	2'308	4.3	163%	
FFF	Level IIIa	99	4'313	3'171	5.9	64%	
GGG	Level IIIa	114	4'473	NC	5.0	100%	
HHH	Level IIIa	128	5'086	4'194	5.7	66%	
III	Level IIIa + Kr2	145	6'500	NC	6.8	161%	
JJJ	Level IIIa + Kr2	325	16'000	NC	9.4	141%	

Figure 7. Table highlighting the different design criteria for a Body Armour Solution. The En.DCC (N.mm) has been highlighted with a colour scale



**Figure 8.** Graph highlighting solutions according to F.EP in N and En.DCC in N.mm (3<sup>rd</sup> trial) and their associated levels of ballistic performances

Several implications arise from this understanding:

Careful consideration is necessary when establishing thresholds for comfort below which body armour is deemed acceptable and above which it is considered uncomfortable. The primary function of body armour is to ensure protection; hence, comfort and mobility acceptance levels must be defined relative to the protection it provides. Body armour manufacturers will thus define comfort levels for different ballistic protection requirements as well as eventually end-user experience.

Furthermore, the data obtained from these three testing methods can enable assessing the trade-offs between ballistic protection area and user comfort, particularly in evaluating how the ballistic protection area can be enlarged by the body armour manufacturer thanks to the use of more flexible materials.

While data from these three different methodologies frequently align, it is important to examine their outcomes concurrently. Each method—Edge Pressure test, which evaluates pressure distribution and its impact on comfort; Lower Costal Bending test, which assesses the resistance of materials to bending forces; and Double Curvature Compression test, which investigates material behaviour under complex compressive loads—provides a distinct perspective that enriches the overall understanding of comfort and mobility. Therefore, a multifaceted approach incorporating these complementary testing methods is ideal for developing products that effectively address the diverse needs of users.

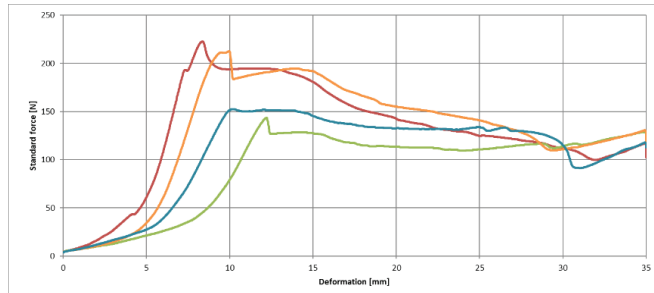
#### 4.3 Material provider results

Within the framework of this study, four different products in the developmental phase, using similar structures but different raw materials, have been evaluated using the Double Curvature Compression (DCC) test. The primary objective of this assessment was to identify the structure exhibiting the highest degree of flexibility and to facilitate the selection of raw materials that would most effectively enhance flexibility in the final application.

The typical Force (N) versus Deformation (mm) curves, obtained through the DCC testing, are presented below. These curves demonstrate significant variances among the four evaluated solutions, which can be attributed by the analysis of the area beneath the curves. The results of this analysis are quantified in N.mm, enabling a successful guidance in the development of the structures under investigation.

Product development can at an early stage use these test methods to consider comfort aspects in addition to ballistic performance and further production and commercial constraints.

In the below example and for this specific material, two curve sections can be distinguished: 1. The energy needed (N.mm) leading to the main fold on the soft ballistic insert; 2. The energy needed (N.mm) to further conform the folded soft ballistic insert to the double curvature shape. More flexible materials may show a less pronounced first peak before propagation of folds.



**Figure 9.** Force (N) Deformation (mm) curves obtained with the DCC for four different products using similar structures but different raw materials

#### 4.4 Test methods availability & accessibility

To ensure that each participant in the value chain is provided with adequate access to these testing methods, continuous communication was fostered among all stakeholders. In this context, Hohenstein Laboratories was identified as a pivotal partner, offering independent testing solutions. Their involvement aimed to facilitate the testing process, provide comprehensive reports, and potentially equip stakeholders with the necessary methodologies for thorough evaluation and assessment of their materials and products.

#### 4.5 Scope of use and path forward

The above test methods and approaches described are focused at evaluating the impact of the soft-armour ballistic protective material assembly on comfort and mobility. The soft ballistic panel assembly is one of the main contributor to comfort. Nevertheless, the additional impacts of rigid insert plates, body armour vest carriers as well as the shaping to enhance fitting for female end-users is to be considered.

##### 4.5.1 Complete ballistic armour vest assessment in conjunction with plates and outer vest carrier

The Edge Pressure test indicates that while the influence of a plate is in many cases limited, the relevance of the test persists, as the localized edge pressure generated by the soft ballistic insert remains significant.

The Double Curvature Compression (DCC) test methodology is incompatible with the use of a plate and therefore does not allow to effectively assess the impact of the plate. However, to enhance mobility, the conformability of ballistic inserts continues to play a crucial role when utilized alongside rigid plates. In that context, DCC should still be capable to discriminate the relative impact of using different soft-armour ballistic solutions when used with the same insert plates.

The Lower Costal Bending (LCB) set-up on the other allows to test complete body armour systems including the insert plate and highlights the importance of the flexibility of ballistic inserts, even when used in conjunction with plates. Preliminary investigations have indeed demonstrated the feasibility of evaluating complete vest solutions, which encompass the ballistic insert, outer carrier, and insert plate. Note that outer carrier designs can also be tested independently from the soft body armour inserts for comfort optimisation of this component. Nevertheless, further validation of the testing procedures including the positioning of the samples is required to ensure that they accurately correlate with user comfort perceptions during actual use.

##### 4.5.2 Ballistic armour female vests

The Edge Pressure test is pertinent for evaluating both male and female body armour, as it effectively assesses pain and pressure points at the vest edges while being minimally influenced by the overall shape of the vest.

Regarding mobility, the assessment becomes more complex with female vests. The Double Curvature Compression (DCC) test can however still be applied to evaluate the conformability of the assembly of constituent materials, given that the multi-axial deformation capability of the ballistic insert is likely a critical factor for the comfort of female vests. Nonetheless, this test does not provide insights into the effects of female-specific shaping techniques.

The Lower Costal Bending (LCB) test can on the other hand generally be utilized in its current form to discern the effects of female body-shaped inserts. To enhance testing methodologies tailored to

female body armour, collaborative efforts with end-users will be essential to develop eventual upgrades to the test set-up that could for example leverage proprietary body shape designs.

## 5. CONCLUSION

The design and assessment of body armour necessitate a meticulous balance between comfort thresholds and ballistic protection levels, given that the primary function of such armour is to safeguard the user while facilitating mobility in various scenarios. This balance requires manufacturers to establish comfort parameters that are aligned with the varying levels of ballistic protection, drawing insights from the experiences of end users. A multifaceted approach is highly valuable, particularly through the application of distinct testing methodologies—namely the Edge Pressure, Lower Costal Bending, and Double Curvature Compression tests. Each of these methodologies offers a unique perspective on material performance, contributing to a comprehensive understanding of how body armour interacts with the wearer's body under different conditions.

Moreover, it is critical to acknowledge that the perspectives on comfort, flexibility, and overall performance provided by these testing methods do not necessarily correspond with traditional weight assessments which allow a more complete overall comfort evaluation from the wearer's standpoint. During the tender adoption process, the insights gleaned from these testing methodologies become instrumental for end users, equipping them with the necessary information to make informed decisions regarding the optimal balance of protection, comfort, and mobility that meets their specific operational requirements.

This analytical framework is essential for both manufacturers and users as it facilitates the evaluation of trade-offs between enhanced ballistic protection and user comfort. By optimizing material design and vest configuration in light of these findings, manufacturers can achieve superior effectiveness to align with end-user specifications. Ultimately, the nuanced understanding of these dynamics is pivotal for developing body armour solutions that effectively address the diverse and evolving needs of users, ensuring not only safety but also operational efficiency and user acceptance in the field.

## Acknowledgments

We thank all the Ballistic Armour Manufacturers and End-Users for their collaboration and valuable inputs enabling this implementation methodology of Comfort & Mobility assessment test methods.

Christophe Chabert, Guillaume Coulboux and Olivier Mauzac from the French MOI are particularly acknowledged for their feedback and support.

A special acknowledgement goes to Jeremie Maurin for the set-up of test design concepts, the assembly and manufacturing of test-rig elements, as well as for leading different testing campaigns. Nicolas Pont, Hakim Hoepffner, Philippe Caudoux and Michel Demolis are acknowledged for their support and technical contributions without which this work would not have been possible. Jan Beringer and Christine Lörcher from Hohenstein are acknowledged for their contribution in the development of the hyperbolic paraboloid test method. Ben Kennedy is warmly acknowledged for his support and interest in this project. Finally, Steven LaGanke and Joe Hovanec are acknowledged for their trust, sponsorship, and support of this project.

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