Body Armour Comfort & Mobility Assessment

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Abstract. With the increased use of protective equipment, the notion of comfort & mobility becomes ever more important to reduce the strain imposed on the wearer. Considering the weight reduction of body armour made possible thanks to the development of increasingly protective material performances, comfort becomes a grail within reach when designing new protective body armours. This however requires capabilities to assess body armour comfort characteristics that are easier to implement than wear trials. Wear trials indeed allow the relative comfort of body armours to be characterized, but these are cumbersome to organize. Unfortunately, previous attempts to develop smaller scale laboratory test methods have proven to be unsatisfactory and shown to be rather poorly related to wear trial results. Various test methods have been explored and will be exposed to come up with reliable and accessible solutions that show good correlation with wear trial results. In this process, a variety of in-use situations, representative of the major discomfort and mobility constraints experienced by body armour users in the field, have been considered. Possibilities and limitations of lab-scale ballistic pack testing are discussed, mostly versus small scale individual body armour testing and wear trial testing. For all test methods explored, the human torso physiological characteristics in terms of shape and mobility have been at the core of the test method concepts and designs. Physiological criteria have also been used to define comfort and mobility criteria related to the discomfort in situations experienced by body armour users. Both 3D optical deformation measurement as well as mechanical test method results are presented. Based on this, a path forward is suggested for implementing new body armour assessment methods using accessible laboratory testing to assess flexibility of ballistic solutions in various situations. The presented methods allow a non-subjective numerical ranking of comfort criteria of body armours in good correlation with wear-trial results. It is also shown that when using various ballistic pack constructions with identical ballistic performances, significant impacts on comfort and mobility can be obtained. Novel solutions using new material offerings show that dramatically increased flexibility, mobility and comfort for the body armour wearer are possible when tools and criteria such as those presented here are used and taken into account in the selection criteria and solution design processes.

1. INTRODUCTION

1.1 The importance of comfort & mobility assessment

Body armour selection is to some extent a tradeoff between ballistic protection and wearability. As of today, the discomfort and mobility constraint of a ballistic vest, highly correlated to the lack of flexibility of a vest, are generally proportional to the level of ballistic protection it provides [1]; therefore, ergonomics, which is a combination of comfort and mobility capabilities, generally decreases as the protection level increases.

While ballistic performance of the material and design of a body armour can easily relate to the protection level, ergonomics, still play an important role in this area. An increased level of comfort, which limits discomfort and painful movement, enables a more systematic use of the vest while higher mobility, which limits movement restriction or energy spent during motion, provides more efficiency on the field, less exposure to risky situations and being less prone to musculoskeletal injuries.

Pope at al's [2] broader literature survey clearly demonstrated that body armour does have significant impacts on physical performance and biomechanical constraints on the wearer. On the other hand, they also determined that effects of body armour on marksmanship and physiological response had not yet been adequately ascertained. Their conclusion was that body armour should be carefully selected, taking into consideration the ergonomics and impact of the body armour on the perceived and measured exertion it induces as well as the impact on work capability, balance and stability.

Through the Functional Movement Screen (FMS) tool, in which scoring is based on different types of movements (involving overhead squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, push-up, and rotary stability), different vests have shown significant differences regarding comfort and mobility properties, mostly on in-line lunge, shoulder stability and rotary stability [3, 4]. In addition to FMS results, time to execute certain movements during end-use situations (e.g. enter and exit of police cars) have been shown to be influenced by wearing ballistic vests [5].

https://doi.org/10.52202/080042-0024

Therefore, police officers appear to be tempted to remove their body armour on the job for discomfort reasons as recently verified and reported in a field survey [6]. This tendency would underline the fact that the wearing of body armours is not neutral to the well-being and efficiency of the wearers. Reasons to remove the body armour are mainly heat, similarly to the desire to remove a sweater in hot conditions, but in almost 50% of the cases, discomfort is considered as a main motivator to remove the protective gear. Weight still appeared as a factor, but only in 25% of the cases. In this survey, comfort came out as the most important factor users would consider for selecting their body armour.

Other studies made using military body armour, showed that reduced mobility could impact the movement and posture [7] and reduce the range of motion [8] even with moderate equipment weights. As a result, ergonomics, defined as a combination of comfort and mobility, is expected to not only impact immediate performance, but eventually, in the long run, also increase the risk of musculoskeletal problems.

Although the impact of ballistic vests on comfort and mobility has been established by wear trials in particular, no consensus toward representative and standardized test methods, which would be easier to set up and less subjective in nature, have yet been defined. Therefore, beyond ballistic performance, price and weight, one of the main purchasing criteria for the end-user remains challenging to be assessed in a standard manner. At the same time, body armour manufacturers have difficulties in developing comfortable solutions because of the lack of defined comfort criteria and related accessible test methods.

1.2 How comfort & mobility have been assessed so far?

1.2.1 Weight measurement

Comfort & mobility assessment has been considered through different perspectives these last decades. Only relying on weight initially in an attempt to determine load applied on the body as well as providing a first quantification level, it has quickly shown a lack of exhaustivity when it comes to defining comfort and mobility. In addition to weight, some approaches have been established to define material flexibility and enlarge comfort & mobility assessment. Three of them have been more commonly used in recent years.

1.2.2 Plunger pressure test

To assess flexibility of a material, various tests were measuring the resistance of a plunger pushing a ballistic pack through a hole in a support plate generally over a pre-defined displacement [9]. Although differences can be measured for different ballistic packs, it remains challenging to correlate these differences to real comfort & mobility feelings perceived during a wear trial. Through multiple end-users' feedbacks, ranking of materials obtained through this test did not correlate well with wear trials using the same ballistic packs. As a result, several initiatives have led to adjust and modify the test procedure to improve the correlation, but none have to our knowledge led to fully satisfactory results.

Obtaining a full correlation may in fact remain challenging as fundamentally the test principle is originally designed to determine the drapability of single layered fabrics on complex geometries [10], and not for assessing comfort and mobility provided by multi-layered constructions. As a result, the shape of the plunger and the punctual pressure it generates associated with the small displacements for which strength is measured (usually between 2 cm to 4 cm) does not realistically replicate ballistic pack deformations observed in practice when worn by law enforcement or military end-users.

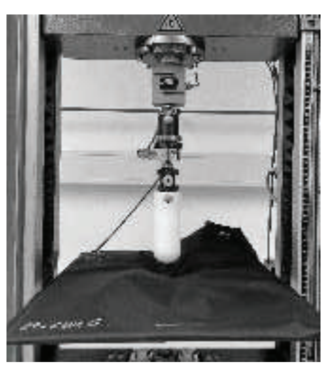

Figure 1. Example of plunger pressure test set-up used in DuPont

1.2.3 Pole or table edge test

Widely used for its ease of setting up, the pole or table edge test consists in measuring the angle formed between a ballistic pack and a horizontal axis. The ballistic pack is positioned on a pole or at the edge of a table. The part not being supported by the pole or the table bends under its own weight. In principle, the more open the folding angle formed by the pack with the horizontal axis is, the more flexible the solution will be [11].

While it can bring a first indication of the flexibility of a solution, results must be exploited cautiously as these do not correlate well with wear trials. The main obvious reason being that a body shape can be considered having a single main curvature but when in movement, it will impose body armour deformations along multiple deformation axes. This occurs when a subject bends forward to tie his shoelaces for example. The pole or table edge test only measures the material's capability to get deformed over one single axis and may thus eventually correspond to how well a body armour may fit while standing but will not correlate with deformations encountered when wearers are in movement. This limitation can be exemplified by the behavior of a sheet of paper that will bend readily on a single axis but will not accommodate to any multi-curvature bending.

Figure 2. Pole single axis flexibility test

1.2.4 Wear trials

Largely used by law enforcement and military forces, wear trials are the most widespread and realistic ways to assess comfort today as it directly connects end-user perceptions during in-use situations. While methodologies are slightly different for law enforcement and military forces, the principle in essence remains the same. Assessing comfort & mobility in a qualitative and quantitative manner through subjective and objective measures.

For law enforcement, typical situations might involve getting in and out of a car, tying shoes, walking, running, handling weights, adopting a shooting position, or typing at the computer. Although the duration of the test can vary between one end-user and another, multiple days of testing are generally performed. During the test, a questionnaire is filled in by each wearer who provides a rating for each different task.

For military forces, obstacle courses are preferred to replicate field situations and constraints. As an example, the Load Effects Assessment Program (LEAP), used by different military forces has been developed to assess impact of equipment on mobility and combat tasks [12]. LEAP consists of a series of different obstacles to be overcome. The impact of the equipment on performance is generally measured through time spent to complete the entire course.

While these tests are highly relevant to define the in-use comfort and mobility impact of equipment, they suffer from several drawbacks. First, they can be quite demanding in terms of resources as multiple wearers are involved for a sustained period. Second, these tests are not fully standardized among the different law enforcement and military forces which makes it challenging for the industry to define a reference or representative procedure. As such, wear-trials in tenders are difficult to be used as a requirement that the equipment suppliers could implement to optimize their offerings.

1.3 How could comfort & mobility assessments evolve?

An ideal comfort & mobility assessment tool should address all the different weaknesses of the various testing methods underlined previously and be easily implemented preferably as a lab-scale test. Comfort & mobility being highly related to material flexibility, this material property would have to be assessed in different ways that correlate end-use situations. An important criteria though, is that the starting point of new tests aimed at correlating well with wear trials, should take into consideration situations met in day-to-day use, the associated movements, as well as the body shape of the wearer. It is likely that only by considering these two elements, test outcomes could eventually correlate satisfactorily with wear trials.

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If such tests are eventually to be used as future standards for comfort assessment in tender processes, as well as for the development of optimized body armours by the industry, the test methods should be kept as simple and easy to set-up as possible. It is indeed important to ensure results can be replicated by end-users as well as by the rest of the value chain in their own facilities.

2. APPROACH TAKEN

2.1 Objectives

The aim of this study is to propose new appropriate laboratory test methods to assess comfort & mobility that would be in line with wear trial testing results. The target being to reproduce quantitatively differentiated and easy to interpret results.

2.2 Principle

The test methods are conceived not starting with existing material testing procedures but are developed based on body behavior, movement, and situations. As a reference, a specific and tailored wear trial has been led to assess the impact of different ballistic vests on comfort & mobility. This wear trial has enabled the identification of dominant wear constraints. Based on these, suitable prototype laboratory test methods are proposed to replicate the most impactful pains and mobility constraints underlined.

3. EXPERIMENT

Three different ballistic solutions have been considered in the frame of the wear trial with different levels of comfort. The ballistic solutions have been designed to pass a given identical ballistic threat and are thus compared at iso-performance, namely according to a NIJ06 level II requirement against 9 mm ammunition with a V50 of 500 m/s and a back face deformation < 44 mm. The three solutions, noted A, B and C are made using different ballistic protective materials and constructed as 100 % mono material assemblies with as a result, differentiated weights and rigidities.

The shape of the vest was identical for all samples and the ballistic packs were inserted into identical carriers. The shape used is representative of typical police ballistic body armours and was designed according to a NIJ medium size C3 design [1].

The wear trials have been led as a blind test with 8 male participants with a height ranging from 170 cm to 185 cm, a weight ranging from 70 kg to 85 kg and an age between 36 and 58 years old.
Each wear trial had a duration of 60 to 120 minutes to allow for detailed feedbacks. Vests B, C and A have been tested in that order with the exact same order for each participant.

To define in-use situation scenarios to be included in the wear trial, feedbacks from law enforcement forces have been considered to replicate the most occurring standard situations to be as close as possible to real life experiences. Some situations were adjusted to enhance the potential impact of wearing a body armour, such as standing up from a lying position, starting from lying on the back rather than from lying on the front. Nine end-use situations have been considered to assess comfort and mobility behavior and were split as follow: office work, driving, tying shoes, standing still, handling weights (picking-up a bag from under a table), body search, walking/running, two-handed handgun shooting position, standing-up from a lying position on the back.

For each situation, a question related to comfort as well as a question related to mobility was asked. Each question got a qualitative feedback as well as a quantitative rating between 0 and 10. On the comfort scale, 0 to 2 referred to a very limited perceived discomfort, 3 to 6 referred to a definable level of discomfort, and 7 to 10 referred to a definable level of pain. On the mobility scale, 0 to 2 referred to a very limited impact on mobility or range of motion, 3 to 6 referred to a notable level of effort required to execute a task, and 7 to 10 referred to a restriction in the movement to be executed.

To provide an easier overview of the quantitative individual situation results, a sum of all the participant ratings has been made for each vest. The sums combine all different situations assessed for respectively the comfort and the mobility feedbacks, which allows for a relative performance rating of the vests. The results from vest A, the least comfortable one, have been taken as a reference with a total rating scaled to a value of 100.

The different ratings and feedbacks have in parallel served as a baseline to identify major pains and mobility issues and used to propose tailored test methods addressing the prominent issues. These test methods are described in the results and discussions chapter in their respective dedicated sections.

4. RESULTS & DISCUSSION

4.1 Wear trials results

4.1.1 The most challenging situations highlighted

The tailored wear trial has enabled the definition of several univocal statements. Overall, the most challenging situations which have been highlighted when it comes to the body armour impact on comfort are recovering from a lying position, tying shoes, handling weights, driving, and performing body searches as reported in Figure 5. These situations are often involving multiple body movements in parallel such as bending, squatting, and/or twisting. Vests A and B are the ones which have most impacted these situations and associated movements.

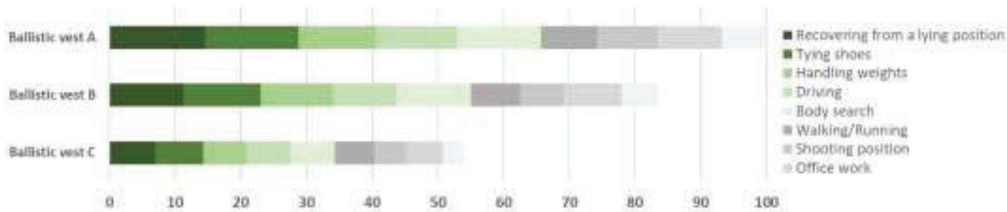


Figure 5. Wear trial discomfort assessment results for vests A, B and C. The relative impact of each situation on comfort is given by the width of each associated colored segment

From a mobility standpoint, differences between vests were in-line with the comfort assessment, with situations such as recovering from a lying position, driving, or tying shoes being reported as the most problematic ones, as described in Figure 6.

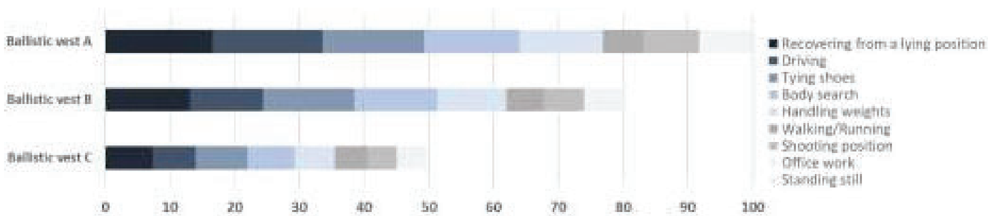


Figure 6. Mobility constraint assessment results for vests A, B and C. The relative impact of each situation on mobility is given by the width of each associated colored segment

4.1.2 Most recurrent pains and mobility constraints

For solutions A and B, most recurring were pains at the arm and shoulder locations due to the pressure exerted by the body armour edges affecting comfort. During the wear trial, these have been highlighted as number one in terms of intensity and occurrence in most of the situations although similar pains have been encountered at the lower abdomen and the neck. From a mobility standpoint, lower back and abdominal mobility constraints have been reported as problematic in executing multiple types of movements such as those described previously.

Figure 7. Pains and mobility constraints for vests A and B

https://doi.org/10.52202/080042-0024

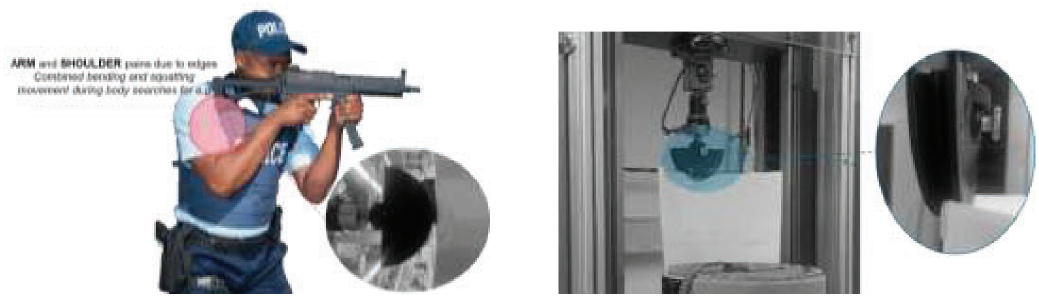
4.2 Edge test design

4.2.1 Introduction

Wear trials have highlighted that the arm, shoulder, lower abdomen, and neck are locations of major pains encountered by the wearer. To provide a first quantification of this pain, it is proposed to replicate body parts and movement into an easy to set-up laboratory test configuration.

4.2.2 Description of the test

The arm is simulated by a semi-circular upper grip which is mounted on a tensile machine. The ballistic vest is replicated by a ballistic pack positioned with a radius corresponding to a typical body shape and upper-torso curvature. The lower grip holding the ballistic pack at its bottom edge is thus curved and allows for a free distance of the ballistic pack corresponding to approximately half the distance between arms, i.e. 20 cm. The semi-circular upper grip is shaped with a pulley profile to maintain the ballistic pack in place during the test. The pressure which is generated by the arm on the ballistic vest edge, in the vicinity of the shoulder-strap of the vest, is replicated by the force applied by the upper grip on the ballistic pack. When positioned at 90 degrees, the physiological mobility of the arm moving towards the front is typically estimated to be of 10 mm after contact with the body armour edge. The test is thus run as a compression test spanning over 10 mm, compressing the ballistic pack while pressing on its edge. Five successive tests have been run for each of the three ballistic packs. A preload of 5 N is applied before recording the force developed in Newton over a displacement of 10 mm.



(A) (B)

Figure 8. (A) Edge test replicating pain occurring at the shoulder and (B) edge test set-up

4.2.3 Results of the Edge test

For certain types of material, it has been shown that the ballistic pack “softens” after multiple solicitations as shown in Figure 9 for packs A and B. The fifth measurement has been considered to represent stable conditions and are used for the analysis. Using the maximum force required to reach a 10 mm displacement thus shows clear differences between the three tested ballistic packs without ambiguity and with a ranking identical to the wear trial results. In the fifth measurement cycle, the maximum strength reached under a 10 mm displacement for ballistic pack A was 125 N, while it was of 53.7 N for ballistic pack B and 27.5 N for ballistic pack C.

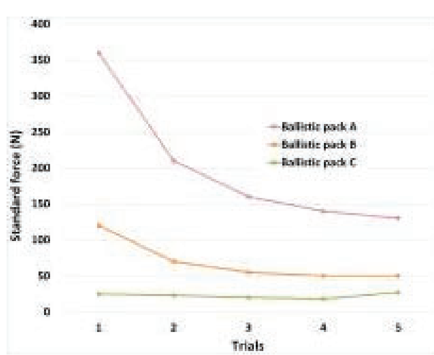


Figure 9. Maximum strength (N) evolution in consecutive tests from 0 to 10 mm displacement

4.2.4 Limitations and next steps

The test method established with a prototype set-up has proven to be easy to use and to be reproduceable even if minor practical optimizations are still in consideration. The procedure of the test, however, would benefit from additional care. In particular when defining if, and eventually how a physiological mobility limitation, such as a maximum strength that can be applied by the body before a pain threshold is reached, should be implemented as illustrated by the orange area in Figure 11.

For each of the three packs, five tests have been made to consider material fatigue and assess the tendency of the pack to get softer after multiple solicitations. It has not been clearly defined which maximum strength can be generated in real situations by the body and if the threshold leading to softening of the material can in fact be reached in-use. As an example, during the 1st trial, the compression force of ballistic pack B that led to softening of the material reached 120 N as shown in Figure 11. Further assessment needs to be made to understand if this level of strength can be applied by the body.

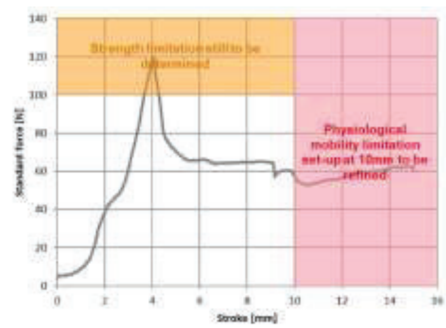


Figure 11. 1st measurement made with ballistic pack B showing limitation and future assessment work to be conducted

4.3 Bending test design

4.3.1 Introduction

Discomfort and mobility constraints are also related to the effort required to perform certain tasks and the constraints on free movement imposed by the rigidity of the body armour. A particular situation where such constraints become most evident is for example tying shoes or getting up from a lying position on the back. In these cases, the main deformation of the body armour and resistance to movement is the forward bending of the upper torso. Trying to stay as close as possible to the body and motion as for the edge test described above, a full-size torso manikin was built, able to fit a standard body armour. The aim is to allow a direct measurement of the resistance a body armour would impose on the upper torso during a forward bending movement.

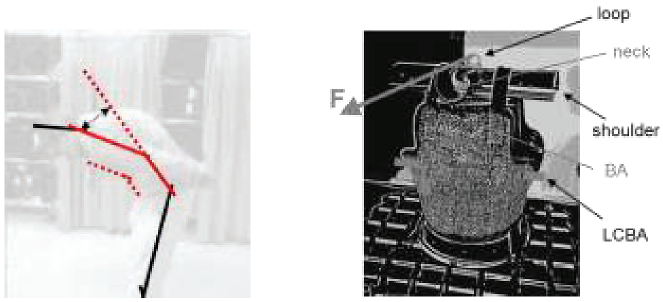
4.3.2 Description of the test

The human upper torso is in fact not a rigid element as it will curve thanks to the flexibility of the spine in the back. In the front, however, the ribcage and sternum inhibit a regular bending deformation in the upper torso region. In the abdominal region, effective bending is also limited due to muscular tension developed during the effort. When schematizing the torso deflection at the front, one can consider two rigid parts with a main bending axis in the lower costal region slightly below mid-height of the upper torso as depicted in Figure 12(A). A prototype bending manikin was built following this schematic, with two cylindrical bodies articulated with an axis at two fifth of the total height. The lower part of the manikin is fixed to a table and the upper part of the manikin is pulled forward with a cable attached to the neck element illustrated in Figure 12(B). The cable is connected to a universal tensile tester machine load cell, allowing translation of the horizontal pull force on the rig to a vertical pull force on the load cell by passing over a pulley fixed to the tensile tester frame.

When bending forward from a straight to a flexed position, looking at your belt buckle for example, the lower costal bending axis (LCBA) plays a major role in the freedom of movement. There is nevertheless a maximum LCBA angle that can be developed. This was measured at about 33 to 35°, resulting in a forward movement at the neck of about 20 cm perpendicular to the lower torso axis as shown by the arrow in Figure 12(A). Body armours will cover the lower costal bending axis and require large scale deformations in this area. Since the body armour is curved around the torso along a vertical

 https://doi.org/10.52202/080042-0024

axis, forward bending will force the body armour into a double curvature. To allow for such deformations, the body armour needs to be able to conform to such a complex shape or be flexible enough to allow for folding to occur. The deformation pattern of two different vests was verified using a flexible and a rigid body armour with 3D speckle digital image correlation analysis (DIC) using an Aramis Pro set-up with a GOM software, which is illustrated in Figure 13. The flexible body armour showed an extensive deformation distributed over the entire front panel with the formation of folds in the lower costal bending axis region. The more rigid body armour was unable to deform in the center part along the original vertical body axis between the neck and the lower abdomen to adopt the imposed double curvature. As a result, the bending force reached a pain point at the neck before the physiological maximum forward displacement was reached.



(A) (B)

Figure 12. (A) Human body main bending axes in a forward bent position.
The upper torso is bending at a lower costal bending axis. (B) Prototype bending manikin with two cylindrical bodies articulated using the lower costal bending axis (LCBA).

(A) (B)

Figure 13. DIC analysis of the body armour deformation: (A) a flexible body armour will deform similarly to a fabric producing folds, (B) a rigid body armour will not fold forwards and will exert high pressures at the neck and lower abdomen.

The bending test rig is used to determine the impact of the rigidity of a body armour on the discomfort induced by the cumulative required additional effort to perform certain tasks. For this measurement, the front panel of the body armour is fixed to the bending test rig. To avoid impact by relative movement, and thus, friction between the rig and the body armour panel, the upper and lower edges are strapped tightly to the test-rig. This allows measurement of force-displacement curves exclusively defined by the body armour’s mechanical characteristics and resistance to bending into a double curvature shape. Testing was performed using an Instron Universal Tensile Tester equipped with a 2’000 N load cell at a crosshead speed of 100 mm/min and using a pre-load of 5 N. Pack mounting was done cautiously using reference positioning and tightening points. Force and displacement data were recorded using a dedicated Zwick software. Data were exported to Excel, treated and analyzed separately.

4.3.3 Results of the Bending test

During the first bending, the body armour packs undergo a first larger scale deformation resulting in “softening” of the panel. Softening however develops rapidly as of the second test cycle and the third solicitation has been used to compare the different materials. Figure 14 shows the distinct behavior in the force-displacement recording of the three ballistic pack constructions evaluated. Rather than testing over a maximum range of motion, it was chosen to limit the test to a neck displacement of 100 mm, i.e. half of the maximum displacement as determined previously which is considered as being more representative of the most common movements.

Double curvature bending of the ballistic protective body armour, as occurring during use, allows clear differentiation between ballistic pack constructions using different materials with varying rigidities. To quantify the impact a body armour may have on the wearer, one can compare forces at a given displacement illustrating the immediate response during solicitation in occupational specific tasks. For a longer-term impact eventually leading to exertion, the energy required to bend the ballistic pack can be compared. Results are shown in Figure 14 below.

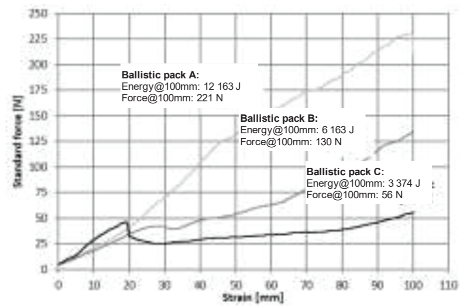


Figure 14. Force displacement curves of the third loadings of ballistic packs A, B and C

It can be seen that at a mid-range displacement compared to the body bending capacity, vests C and B require respectively about a quarter and half of both the force and energy needed to bend vest A. This difference is significant and would be expected to impact both immediate response during tasks as well as longer term cumulative exhaustion upon repeated or intense activities. This correlates very well with the wear-trial responses that also clearly differentiated the comfort and mobility perceptions of the three vests with similar magnitudes.

4.3.4 Limitations and Next Steps

Although the prototype bending manikin and test set-up appears to yield consistent results, it is of interest to attempt to simplify the test method. The current set-up would for example suffer from the fact that it can only be used on a dedicated set-up, not fully incorporated into the tensile tester. Nevertheless, to evaluate the impact of body armour ballistic pack design and material assemblies, the current evaluations indicate it is important to test body armours in a double curvature configuration. As a next step, a target is to develop and evaluate a simpler double curvature deformation test method that may be used directly on a universal tensile testing machine but would still respect physiologically defined body shape curvatures. This effort is in parallel pursued as a partnership with Hohenstein focused at developing a test method design starting from the Hyperbolic Paraboloid shape that replicates the body double curvature while bending. Mounted on a tensile machine, it would allow to measure the energy required to bend the ballistic pack into a double curvature in a simple way.

Figure 15. Illustration of a DuPont and Hohenstein prototype Double Curvature Compression (DCC) test method using a Hyperbolic Paraboloid shape to simulate the bent upper torso principal curvatures

5. CONCLUSION

Although the impact of ballistic vests on comfort and mobility has been identified by end-users and many wear trials, key factors involved in the perception of comfort and mobility have not been systematically defined and thus no consensus toward any representative or standardized test methods that would allow a rapid assessment of body armour comfort has been established. The approach taken to address this gap was to first, run a dedicated wear trial aiming at identifying key comfort related complaints and, to develop new test methods starting from human body and movement rather than using or adapting existing material test methods as has been attempted in the past. These new test methods, designed specifically to mimic the interaction between a body armour and the human body in movement, allow for a more

https://doi.org/10.52202/080042-0024

realistic assessment of in-use effects that wearing of body armour vests may have. The wear trials were led with a focus on the definition of comfort issues and mobility inhibition factors perceived by the wear-trial candidates. Two main factors came out as the most prominent affecting comfort and mobility. These were the pain provoked by the body armour edge pressing on the arm, abdomen or neck, and, the mobility constraint imposed by the rigidity of the ballistic pack on the torso. The origin of these issues arises mostly from the ballistic protective material assembly used within the ballistic pack inside of the body armour vest. The vest shape and design may help mitigate some issues but will not intrinsically solve these and may lead to compromising on the ballistic protection coverage. It was thus chosen to focus on the phenomena observed and the ballistic pack material's response for developing laboratory testing methods and procedures, allowing to anticipate body armour comfort and potential mobility issues before having to run wear trials that are long and complex to organize. Two test methods, which take into consideration the body shape of the wearer as well as situations met in day-to-day use and the associated movements, were developed. These are the Edge test and the Bending manikin test, both of which showed reproduceable results and were able to clearly differentiate the body armours tested in terms of comfort related responses. The obtained results were in-line with the wear trial feedbacks.

As a next step, design optimization for each of these tests is being pursued to further simplify implementation on standard universal tensile testing machines. The test procedures and analysis will also be refined taking into consideration further physiological parameters, such as pain thresholds or ranges of motion. The target is to ultimately enable and facilitate the accessibility of such tests and allow easy implementation by end-users as well as the value chain actors involved in supplying body armour solutions. Therefore, frequent exchanges and feedbacks from end-users and value chain partners will continue to be valued and taken into consideration to ensure relevance for all stakeholders interested in body armour comfort.

Acknowledgments

A special acknowledgement goes to Jeremie Maurin for the implementation 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. Antonio Recchia and Simeon Frei are acknowledged for all the learnings and knowledge shared in the 3D image analysis. Eoin Lynch and Adriano Mendonça are acknowledged for the insightful exchanges and relevant inputs. Ben Kennedy is warmly acknowledged for his support and interest in this project. Eoin Pierce and Connor Sheehan are gratefully acknowledged for reviewing this paper and the relevant feedbacks provided. Finally, Steven LaGanke and Joe Hovanec are acknowledged for their trust, sponsorship, and support of this project.

References

[1] Sabol W.J., Tillery C., Stoe D. and O'shea M., Body Armor Guide (National Institute of Justice, USA, 2014).
[2] Tomes C., Orr R.M., and Pope R., Annals of Occupational and Environmental Medicine, 2017; 29;14.
[3] Schram B., Orr R., Hinton B., Norris G. and Pope R., J of Bodywork and Movement Therapies, 2020; 24(3); 190-194.
[4] Tomes C.D. and Lewis M.D., Int J of Exerc Sci, 2019; 12(6); 536-546.
[5] Koblauch H., Zebis M.K., Jacobsen M.H., Haraldsson B.T., Klinge K.P., Alkjaer T., Bencke J. and Andersen L.L., Sensors, 2021; 21(5); 1-12 [1795].
[6] Avient Corp, US law enforcement survey, 2022; www.officer.com/on-the-street/apparel/uniform-fabrics/press-release/21289606/dsm-dyneema-dyneema-releases-us-law-enforcement-survey-results.
[7] Phillips M.P., Shapiro R. and Bazrgari B., Ergonomics, 2016; 59; 682–91.
[8] Lenton G., Aisbett B., Neesham-Smith D., Carvajal A. and Netto K., Ergonomics, 2015; 59(6); 808–16.
[9] Horsfall I., Champion S.M. and Watson C.H., Applied Ergonomics, 2005; 36; 283–292.
[10] Kissinger C., Mitschang P. and Neitzel M., Materials for Transportation Technology Vol 1 (Wiley-VCH Verlag GmbH, Germany, 2000), Winkler P.J. Ed.; pp. 176-182.
[11] ASTM D1388, Standard Test Method for Stiffness of Fabrics – Option A: Cantilever test, 2018.
[12] Karakolis T., Sinclair B.A., Kelly A., Terhaar P. and Bossi L.L.M., Human Factors, 2017; 59(4); 535-545.