Why is my rifle plate so uncomfortable?

Paul Fenne[1], Tommaso Romano[2], Tim Williams[2], K. Tomczyk[2], Dirk Landheer[2]

[1] *Physical Protection Group, Metropolitan Police, Olwen House, 8-20 Loman Street, London SE1 0EH*
paul.fenne@met.police.uk
[2] *Simpact Engineering Ltd., Unit 2, Trojan Business Centre, Tachbrook Park Drive, Warwick CV34 6RS, United Kingdom, tommaso.romano@simpact.co.uk, tel.: +44 (0)1926 498620*

Abstract. The perceived comfort level of hard plates used as ballistic armour affects the mission effectiveness of the wearer; however, due to manufacturing challenges and lack of clear ergonomic requirements in the current standards, most of the currently produced plates have a relatively flat and uncomfortable shape, not based on a realistic torso shape.
This paper details the efforts in Metropolitan Police Service to define an ideal shape to give the best wearability to a wide range of users. A first prototype ergonomic chest plate was derived from a 3D scan of a male chest, in such a way to ensure correct anatomic proportions and optimise the pressure distribution on the torso.
The prototype chest plate underwent a supervised shape fitting assessment at Metropolitan Police Service Training Centre (MPSTC) involving 47 test subjects, both male and female. The prototype demonstrated to be a good fit for two thirds of police officers. The geometry information on the torso of the police officers was acquired by means of non-contact 3D laser scanning, and a high-level statistical analysis was carried out on their height and bideltoid breadth. This data will be subsequently used to derive an anatomically correct chest plate geometry and could be used to carry out virtual wearability assessments of ballistic plates and other equipment.
The positive outcome of the shape fitting assessment of the prototype chest plate demonstrates that a comfortable chest plate shape needs to be based on a realistic torso geometry, and confirms the suitability of the applied techniques to this project. This study thus aims to set the basis for a new generation of ergonomic armour that will enhance the comfort and mission effectiveness of the wearer.

1. INTRODUCTION

Police officers and soldiers throughout the world rely on chest plates to protect them from high-powered rifle bullets. Although there is variability in plate shapes and materials, the overwhelming majority of chest plates include a rigid component – usually a type of high-performance ceramic – that, due to standardisation and manufacturing challenges, is often produced in a relatively flat shape. If that shape does not match the organic curvature of the human body, the plate will be regarded as uncomfortable by a significant percentage of users [1].

The study presented here is part of a long-term feasibility study aiming to identify the characteristics that make a chest plate comfortable. Although the authors are aware of the current technological and manufacturing constraints, these are not considered in the current analysis. These limitations will be addressed in a future study.

1.1 The contributing factors to protection

The end goal of any personal armour system is to protect the user from a ballistic threat, and there are several body armour standards that establish the minimum ballistic resistance of plates falling under certain categories [2][3]; however, ballistic resistance is just one of the required characteristics to guarantee the best chance of survival to the user.

Another key aspect is the coverage provided by the chest plate: no armour system can provide protection against bullets that do not impact against it. Although the logical implication of this conclusion would be to increase coverage as far as practically possible, this conflicts with the requirements of mobility and wearability: a cumbersome body armour system is going to hinder the wearer's ability to fulfil his mission, and could – by slowing down the user – expose him or her to enemy fire for a longer period than necessary. The consolidated approach is thus to cover the upper part of the torso, approximately from the suprasternal notch to the floating ribs. The chest plate should thus be able to effectively protect the heart, aortae, spleen, kidneys, lungs, liver and stomach (see Figure 1).

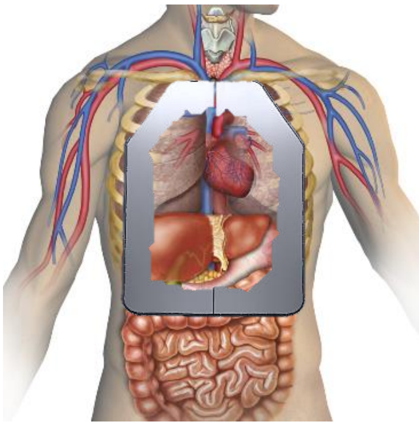

Figure 1. Chest plate showing vital organs in the human chest

The final, and often critical, contributing factor is comfort. Although this might be easily overlooked, comfort is what ultimately drives the likelihood of the chest plate being worn when most needed. This factor is directly connected to the scope of this study: a chest plate that does not fit properly is less likely to be willingly worn by the end user during his or her daily activities, possibly leading to catastrophic outcomes.

The overall chance of protection provided by a chest plate is thus given by the product of the described factors: an uncomfortable chest plate which is worn only 30% of the time, even if capable of stopping 100% of the threats and covering 100% of the vital organs, will provide just 30% of overall chance of protection.

Furthermore, even when the plate is actually used, an unsatisfactory fit is going to hamper the movements of the wearer and could result in discomfort, which degrades the physical and mental performances [4][5] thus reducing mission effectiveness.

Of the three contributing factors that were highlighted (ballistic resistance, coverage, comfort), this study focuses on the latter. Significant research has been focused on ballistic performance [6], potential injuries and ergonomics [7] (that drive the coverage). However, comparatively fewer studies have investigated wearability (comfort).

Since the probability of a chest plate being worn is directly related to its perceived comfort, improving this aspect increases the likelihood of wearing of the plate and, ultimately, saving lives.

1.2 Historical background

Since the dawn of man, armour and weapons have simultaneously evolved to get an advantage over each other, in an arms race which has not seen its end yet.

Although both competing categories saw a radical technological advance, from sticks and stones to assault rifles and from padded furs to multi-layered composite bullet-resistant armours, the basic requirements of weapon-resistance, coverage and comfort remain throughout human history. The very first known complete body armour system dates back to the fifteenth century BC, in the late Mycenaean period.

Known as Dendra panoply (see Figure 2) from the Greek village where it was found in 1960, it is mainly made out of bronze – as tough as the best weapons of its era, made of bronze or low-quality iron – thus providing good resistance against enemy blows; it also almost completely covers most of the wearer's torso, neck, shoulders and groin, thus giving excellent coverage.

  

Figure 2. Dendra panoply **Figure 3.** Chain mail armour **Figure 4.** Replica of jousting armour

Most interestingly, it shows a hinged construction that allows good mobility and comfort to the wearer, and the aperture for the right arm (the weapon arm) is significantly enlarged to ensure adequate combat-effectiveness. The panoply, probably belonging to a high-ranking Mycenaean noble, would definitely have provided his owner a significant advantage in combat.

Although admirable for its era, the Dendra panoply still showed significant ergonomic drawbacks, namely the entire mass of the armour (15 to 18 kg) is supported by the shoulders. This limitation, which is understandable due to the technological constraints of that time, probably made the armour uncomfortable to wear over extended periods.

A definite improvement in terms of comfort was represented by mail armour, as shown in Figure 3. One of the most widely used types of armour across the centuries, chain mail armour provided an excellent fit and mobility to most users while also allowing unprecedented ease in wearing of the armour. Thus the soldier was able to wear and remove the armour in a few seconds, with no external help. The weight of the armour is now spread between the shoulders and the hips, thanks to the introduction of a belt. This makes the armour much more comfortable to wear over extended periods.

A further step forward is represented by the later suits of plate armour: the fine example shown in Figure 4 on the right is a Milanese style replica of a jousting armour (1450 ca.), optimised for maximum protection. The estimated weight of around 40 kg is carefully distributed over all the body with a clever harness system, and the wearer’s movements are enabled by hinges in the plates.

In recent times, a notable example of armour is the Russian “steel bib” armour, developed in WWII and meant for assault engineers (see Figure 5). Although appreciated in close quarter combat, it was often discarded by soldiers because of the burden it represented during tactical movements, especially crawling.

Figure 5. SN-42 *Stalnoi Nagrudnik* "steel bib" armour

Advances in technology made ballistic resistant plates much lighter and effective; however, the same concerns regarding ergonomics and comfort still apply.

1.3 The modern chest plate

Modern rifle-resistant chest plates belong to one of the following categories: i) inserts designed to complement and fit in an existing body armour system (usually in conjunction with a soft body armour) or ii) chest plates meant to provide stand-alone protection. Chest plates falling in the latter category are usually worn in a plate carrier. The plate carrier, when used with a stand-alone chest plate, does not provide any additional ballistic protection and is usually significantly thinner and more compliant than a soft body armour. In this case the shape and the outline of the plate are even more important to determine the perceived degree of comfort of the body armour.

Figure 6. Typical design of a stand-alone chest plate providing protection against high-velocity bullets

Unfortunately, to reduce design and manufacturing costs and due to the lack of attention to ergonomics, most chest plates currently in production exhibit a relatively flat shape (see Figure 6), which is usually regarded as not comfortable by a significant percentage of users [1].

2. DESIRABLE CHARACTERISTICS OF A COMFORTABLE CHEST PLATE

In order to identify the best design for a chest plate, the two main characteristics are the curvature of the surface which is in contact with the body, and the outline, i.e. the external silhouette of the plate itself. These characteristics are further described in the subsections below.

2.1 Curvature

The plate should be carefully designed to fit around the natural shapes of the human chest. An ideal curvature would spread the weight and pressure resulting from a tightly-strapped plate over the entire chest, thus preventing discomfort due to pressure points and/or chafing. Additionally, a good-fitting chest plate minimises bulk. Hence the mass is concentrated where strictly needed, and closely follows the contour of the body. This has several positive side effects, firstly the plate is less conspicuous and easily concealed, since it does not stand proud of the body and provides a natural, organic external appearance. Furthermore, in a good fitting plate the lateral edges shall be so close to the body as not to interfere with both normal and tactical activities, avoiding snagging and contributing to perceived comfort.

As an ideal chest plate is able to efficiently spread the weight, it is assumed that the mass of the plate would be more tolerated by the users. This claim is supported by both literature [8] and previous experience of the authors, showing that soldiers and police officers are inclined to perceive as “lighter” the more comfortable plates, with only a loose correlation with actual chest plate mass.

The present study focuses on this aspect.

2.2 Outline

The outline of a chest plate is of paramount importance in determining the ease of carrying out daily and tactical activities without being hindered by the plate. Although an in-depth study of the ideal outline is not a subject of this study, some preliminary considerations were taken into account in this paper. The principal of these characteristics is the clearance between the arms. This is important to allow both routine and tactical movements that require one or both arms to be extended forward. Notable examples are driving a car, opening a door, handcuffing a suspect, using a handgun or a torch.

3. FINDING THE IDEAL CHEST PLATE

As a first step towards the ideal chest plate the authors focused on ergonomics, and in particular on the ideal curvature of a chest plate.

The human torso comprises several different types of tissues (e.g. bone, muscles, fat) that offer a different resistance to compression. Bone is obviously the least compliant type of tissue that may be found in the chest. A chest plate in direct contact with bone will create a localised high-pressure area that may generate discomfort. Pressure points are of fundamental concern in comfort evaluation.

The postulate which is driving the study is that an even distribution of pressure on the body is conducive to a comfortable chest plate. This statement is supported by personal experience of the authors, and its validity will be proven by the following analyses.

In order to produce a chest plate able to equalise the pressure acting on the chest, it is important to start with an accurate representation of the geometry of the chest itself. For this reason, the authors investigated the possibility of using a 3D laser scanner to acquire accurate information on body geometry of a test population.

3.1 The 3D scanner as a tool to acquire chest geometry

A 3D laser scanner is a non-contact tool able to analyse a physical object and obtain data on its shape. It works by emitting a pulsed laser beam towards the object to be analysed. The reflected light is received by a sensor, which calculates the delay between the emission of the beam and the reception of the reflected light. Since the speed of light is known, it is possible to obtain an accurate measurement of the relative position of a cloud of points belonging to the outer surface of the object being acquired. Once the data (known as "point cloud") is acquired, it is possible to interpolate the points and create a surface.

Due to its small ranging noise and error [9] and flexibility, a 3D laser scanner appeared to be an ideal tool for the case at hand. The authors thus contacted WMG, part of University of Warwick, which kindly provided a FARO Focus^{3D} X 330 laser scanner and technical support.

Figure 7. FARO 360 Laser Scanner

The scanner (shown in Figure 7) is able to acquire surface information of objects in a full circle, due to its beacon-like revolving head. Although this scanner is designed to acquire large volume data, such as buildings, its characteristics make it appropriate to rapidly acquire body shapes of multiple test subjects at the same time, provided that the subjects are suitably positioned in a circle around the scanner.

Once the tool to acquire the geometries of the body was selected, the authors analysed other aspects that could affect the quality and suitability of the laser scan for the intended purposes.

3.2 The role of clothing in 3D scanning

Since a laser scanner works on the principle of reflection of light, it can be sensitive to the finish of the surface to be acquired. For example, a mirror-like surface is not easily acquired because of the excessive directionality of the reflected beam. Therefore, it was thus imperative that the test population should wear clothes that provide a good quality, non-reflective surface for laser scanning.

A second, important consideration is related to the actual surface of the clothes. Since the goal is to acquire chest geometry, it is important for the clothes to closely follow the body shape, with no creases, folds or visible fastening means (e.g. buttons).

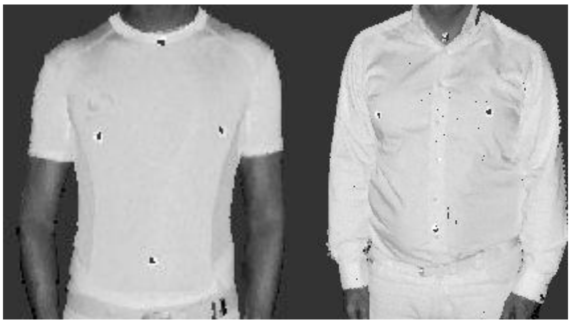

Figure 8. Effect of different clothes on scan quality

An example of the difference is shown in Figure 8. It clearly appears that, because of its loose fit, the clothing worn by the test subject on the right is not adequate to acquire chest geometry.

It is thus necessary, for this type of exercise, to wear tight-fitting clothes that expose the chest shape (see Figure 8, on the left).

Another significant advantage of tight-fitting clothes is the mild level of chest compression they provide. As previously discussed, localised high-pressure areas should be avoided, particularly direct contact with bone structures. A tight T-shirt gently pre-compresses the chest muscles and, at the same time, stands slightly proud of the sternum, which is the main exposed bone of the upper torso. Figure 9 shows a comparison between the scan of a naked torso and the scan on the same torso covered with a tight T-shirt. The compressed areas are shown in blue, while in red it is possible to see the areas of the T-shirt that stand slightly proud of the body.

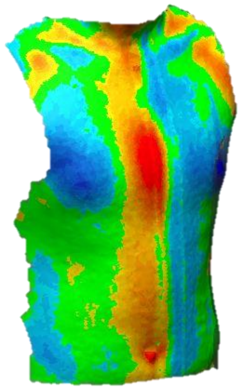

Figure 9. Differences between clothed and naked torso

The resulting scanned surface, while still closely following the body shape, consequently has a slight interference with the pectoral muscles and no direct contact with the sternum: these characteristics can lead to a chest plate which spreads most of the load on the compliant tissues, preventing any hard, uncomfortable contact with the bones.

3.3 First body scanning and creation of prototype

The first body scanning exercise focused on demonstrating the suitability of this technique to the project. Six volunteers were dressed with a variety of clothes, including one volunteer wearing a very tight T-shirt, and their torso geometry was acquired using the FARO Laser Scanner.

As expected, the chest geometry obtained from the volunteer wearing the tight T-shirt was considered the most suited to be used to create a first chest plate geometry.

Starting from the surface of the chest geometry from the 3D scan, a chest plate outline (Figure 10, left) was drawn. The outline is meant to provide maximum coverage, while still allowing normal movements of the torso and arms. A full CAD was then produced, and finally a 3 mm thick prototype for ergonomic and shape fitting assessment was 3D-printed out of black ABS polymer. The thickness is meant to make the ergonomic demonstrator suitably stiff, while minimising manufacturing costs.

Figure 10. Different steps of prototype generation

A first ergonomic assessment was carried out on the test participants. As expected, the plate exhibited a perfect fit for the test subject whose scan data was used to create the plate. However, the chest plate was a very good fit for over half of the sample, even for people with different perceived sizes (see Figure 11).

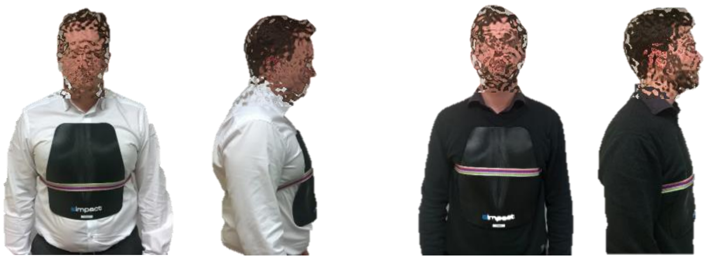

Figure 11. First ergonomic assessment

The first, important conclusion that emerged from this exercise is that in order to generate a comfortable chest plate the body size, although important, is not as fundamental as body shape.

3.4 Body scanning of MPS police officers

The second body scanning exercise took place in the Metropolitan Police Service Training Centre (MPSTC), an operational training unit that granted the authors access to a comparatively large number of test subjects. A total of 47 persons, divided in six groups, were asked to stand in a circle around a FARO non-contact 3D laser scanner (see Figure 12). Both chest and back of the volunteers were acquired.

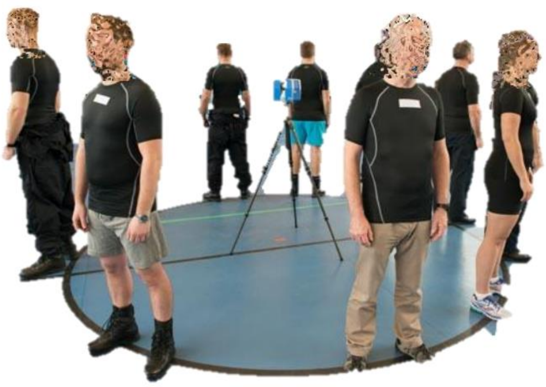

Figure 12. Torso scanning at MPSTC

The analysed population included 45 police officers – of which 7 were female – and two external volunteers, one male and one female. All the test subjects wore tight-fitting shirts to improve scan quality and achieve mild compression of the torso. The acquired scan data was subsequently analysed to measure height and bideltoid breadth of the police officers.

The average height of the analysed population (footwear included) is 181.7 cm for males and 169.4 cm for females. A similar standard deviation is observed for both groups (see Figure 13, top left graph). Since the height of the torso is roughly proportional to the overall height of a person, this data can provide useful information on chest plate dimensions.

Bideltoid breadth is another indicator of the build type of an individual. The average bideltoid breadth in the test population is 47.0 cm for males and 40.6 cm for females. As can be inferred from the top right graph in Figure 13, a much wider spread was observed in the male population: this is due to the higher variability in muscular mass in males, as opposed to females.

The ratio between height and width is another indicator of the build type of an individual. The average ratio is 3.87 for males and 4.17 for females. The results highlight that female police officers usually have significantly more slender bodies.

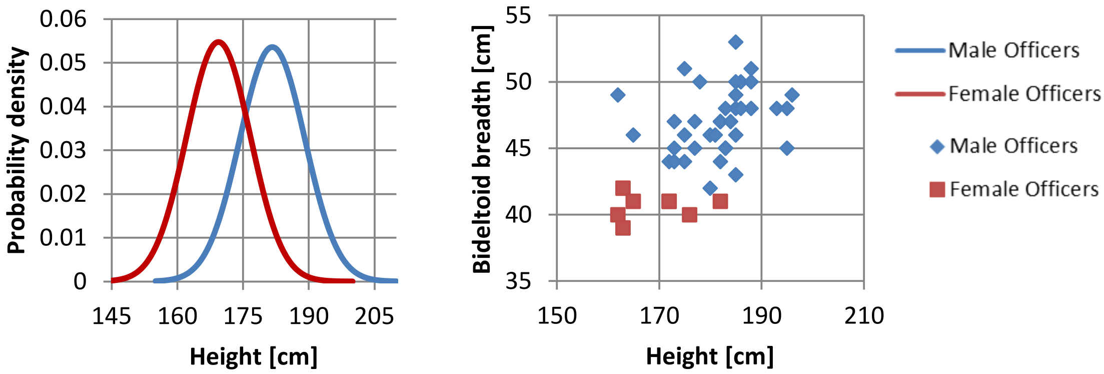

Figure 13. Statistic analysis

3.5 Shape fitting assessment at MPSTC

After the scanning exercise, each of the test subjects was asked to take part in a supervised shape fitting assessment and wear the 3D-printed prototype ergonomic chest plate. This exercise was meant to have an initial evaluation of the plate in terms of shape and fit, and was part of the preparation for an comprehensive wearability assessment. The focus of this study is on stand-alone plates because the lack of soft body armour makes wearability even more critical. As a consequence, no soft body armour was included in the shape fitting assessment.

The test was carried out with the test subjects in a standing position, as shown in Figure 14. This was an open trial based on a single fitting of the plate, which was applied to the body by hand and hand-supported throughout the exercise. The fit of the ergonomic chest plate was assessed by the authors based on the presence or absence of gaps and interferences between the plate and the body. The fit was subjectively rationalised in a four-rank scoring system consisting of the following evaluations: good fit, acceptable fit, poor fit, bad fit.

The results of the assessment can be seen in Table 1 and in Table 2, where the test population has been divided into categories based on gender and T-shirt size.

Figure 14. Shape fitting assessment

Although 39 male subjects were scanned, two of them are not included in the assessment because of insufficient photographic information to evaluate the fit of the plate. The remaining 37 male subjects were further categorised based on their T-shirt sizes, from small to extra-large. Two persons, due to their unusual chest shape, were considered outliers and categorised as “other”.

The ergonomic chest plate appears to be a good fit for 56% of the population of police officers wearing a medium size T-shirt, with an additional 20% finding the shape in need of minor modifications. The fit of the plate appears to be worse for officers wearing large and extra-large T-shirts. Overall, the plate demonstrated a good or acceptable fit for almost 65% of the tested male population.

Table 1 . Ergonomic assessment of male police officers

Males									
	Good fit		Acceptable fit		Poor fit		Bad fit		Total
Small	1	**50.0%**	0	**0.0%**	1	**50.0%**	0	**0.0%**	2
Medium	14	**56.0%**	5	**20.0%**	4	**16.0%**	2	**8.0%**	25
Large	2	**33.3%**	1	**16.7%**	3	**50.0%**	0	**0.0%**	6
Extra-large	0	**0.0%**	0	**0.0%**	0	**0.0%**	2	**100.0%**	2
Other	0	**0.0%**	1	**50.0%**	0	**0.0%**	1	**50.0%**	2
Total	17	**45.9%**	7	**18.9%**	8	**21.6%**	5	**13.5%**	37

Table 2. Ergonomic assessment of female police officers

Females									
	Good fit		Acceptable fit		Poor fit		Bad fit		Total
Small	3	**75.0%**	0	**0.0%**	0	**0.0%**	1	**25.0%**	4
Medium	1	**50.0%**	1	**50.0%**	0	**0.0%**	0	**0.0%**	2
Large	0	**0.0%**	1	**50.0%**	1	**50.0%**	0	**0.0%**	2
Total	4	**50.0%**	2	**25.0%**	1	**12.5%**	1	**12.5%**	8

Similar results were obtained on the female population sample; a good or acceptable fit was found for a total of 75% of the subjects.

A significant variation in the chest shape of female subjects was observed, which caused some instances of the plate not fitting. The information acquired during the laser scanning exercise will be used to generate suitable chest plate geometries to fit the female chest with minimal bust compression. These plates will be tested in an upcoming wearability assessment involving a statistically significant number of female subjects.

In the population sample studied in this test, 4 males out of 39 showed almost exactly the described average dimensions, but they still had remarkably different build types: two of them had lean and athletic builds and the fit of the plate on their chest was found to be good, whilst the remaining two did not have athletic builds, and the ergonomic chest plate did not fit them. The sample chest plate appeared to be a very good fit for the vast majority of subjects that have a lean and athletic build, with only a minor correlation with actual height or shoulder width. The most common comment on the fit of the plate was related to the lower corners, which were sometimes perceived as digging into the rib cage. The clearance between the arms proved to be another potentially critical design variable.

These observations highlight the need to compliment the acquired data with more information, such as body mass, chest circumference and physique.

4. CONCLUSIONS

The presented analysis shows that an ergonomic chest plate purposely designed to even the pressure distribution on the torso of a sample subject can effectively provide a good fit for most of the assessed population. This proves that the pressure distribution is what ultimately drives the perception of comfort or discomfort when wearing a plate.

The difference in shape between a typical chest plate and an ergonomic chest plate is shown in Figure 15. The plate on the left does not offer a good fit, since it is not based on a realistic chest geometry.

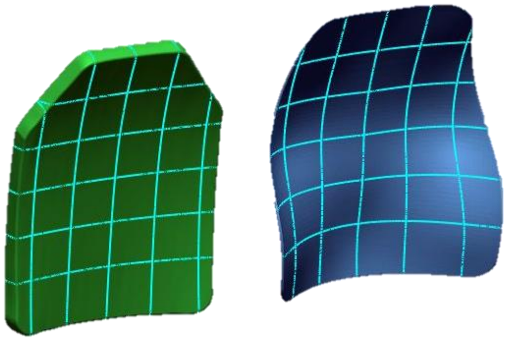

Figure 15. Comparison between existing plate (left) and ergonomic chest plate (right)

A novel approach to achieve an ergonomic chest plate with a good fit is presented. This process is based on the acquisition of real chest geometries by means of 3D scanning, and on the subsequent creation of a 3D chest plate geometry. Furthermore, the possibility of exploiting 3D-printing technology to allow for rapid prototyping and preliminary assessments of the plate is demonstrated.

With some minor modifications, based on the shape fitting assessment, it is believed that the presented plate will be able to achieve an excellent fit for the vast majority of police officers with athletic build types. Further studies and ergonomic assessments are needed in order to determine the most suitable shape for other build types. The 3D scan data can now be used as a guidance to create a new series of 3D printed ergonomic chest plates for use in a more extensive wearability trial, and the same techniques will be applied to develop more comfortable back plates. It will also allow further statistical analyses on body shapes and dimensions, and virtual wearability assessments of equipment.

This study demonstrates that a comfortable chest plate shape needs to be based on a realistic torso geometry, and will be the basis for a new generation of ergonomic armour that will enhance the comfort and mission effectiveness of the wearer.

Acknowledgements

The authors would like to thank Alex Attridge and Mike Donnelly from WMG for their assistance in the preparation and execution of the 3D scanning exercises, Ben Wood from International Institute for Product and Service Innovation (IIPSI), WMG, for 3D printing the ergonomic chest plate, and Paula Romano from Kit Design Ltd. for providing suitable clothing.

References

[1] R. L. Nevin and G. E. Means, Pain and Discomfort in Deployed Helicopter Aviators Wearing Body Armor, Aviation, Space, and environmental Medicine, Volume 80, No. 9, 2009, pp. 807-810(4).

[2] NIJ Standard-0101.06 “Ballistic Resistance of Body Armor”, Standard and Testing Program of the National Institute of Justice (NIJ), Office of Justice Programs, U.S. Department of Justice, 2008.

[3] Croft J, HOSDB Body Armour Standards for UK Police (2007) Part 1, 2 and 3.

[4] C.H. Watson, I. Horsfall, P. Fenne, Ergonomics of Body Armour, Proceedings of PASS2010, 2010.

[5] G. E. Peoples et al., The effects of thoracic load carriage on maximal ambulatory work tolerance and acceptable work durations, European Journal of Applied Physiology, 2016, Vol. 116, Issue 3.

[6] P. J. Hazell, Armour Materials, Theory and Design (CRC 2016), chapters 7 and 8.

[7] J. Astwood, L. Sullivan, C. Kelly, K. Tatlock, Dismounted Close Combat Human Factors Assessment Framework Technical Guide, DSTL, 2014.

[8] J. J. Knapik et al., Soldier Load Carriage: Historical, Physiological, Biomechanical, and Medical Aspects, 2003.

[9] FARO Laser Scanner Focus^{3D} X 330 Features, Benefits & Technical Specifications, 2013.