Relative effect of ballistic plate coverage on the protection system performance

G. St-Onge[1], A. Bouamoul[2], and S. Ouellet[2]

[1]*DRDC Valcartier, 2459 Pie-XI Blvd North, Quebec, Qc, Canada,*
Correspondence: *Gabriel.St-Onge@drdc-rddc.gc.ca*

Abstract. Ballistic plates are designed and fitted to protect vital organs from injuries while maintaining the ability of soldiers to perform their mission effectively. Thus, the design of a ballistic protection system should represent the best compromise between the protection it offers (i.e., the ability to stop a threat and protect organs from life-threatening injuries) and the physical burden it adds to the soldier. The optimization of plate coverage to minimize impact on soldier mobility and comfort is often difficult due to the lack of robust tools to study the effect of changes in coverage on soldier vulnerability. The aim of the study reported herein was to inform this design optimization process by evaluating the impact of changes in ballistic plate geometry on the ability to minimize the risk of life-threatening injuries. The Canadian Operational Research Environment for Vulnerability and Lethality (CORE V/L) software, a numerical Vulnerability and Lethality tool, was used in conjunction with various protection performance metrics (i.e., Average Anatomical Profile (AP) Score, Average New Injury Severity Score (NISS), Maximum Abbreviated Injury Scale (MAIS) mapping, etc.) to evaluate parametrically the effect of changes in the length and width of a plate and its general shape. A range of ballistic plate configurations were therefore simulated and compared in a way that informs designers of the effect of small geometric changes on protective performances. Small changes in the geometry of ballistic plates are shown to affect its ability to protect soldiers from life-threatening injuries. The study also identifies which changes have the largest and smallest influence on soldier survivability. All simulations were performed on an anatomically accurate representation of a 50th percentile human male. Future research will aim to extend recent findings to male and female of different statures.

1 INTRODUCTION

In military settings, ballistic protection protects soldiers against injuries caused by projectile or fragments. Whether it is bullets from a firearm, fragment from shell or grenade, or rock and soil from IED (Improvised Explosive Device) those projectiles can cause significant injury to military personnel. In military conflicts, it was reported that 90% of all injury sustained during military conflict since World War I are caused by penetrating projectiles [1]. This is still relevant in more recent conflict as it was reported that 83% of healthcare specialists in Ukraine have observed penetrating injury pattern from bullets and fragments [2]. Conflicts can also provide some level of information on the protection performances of fielded protective equipment. For example, a study from the Armed Forces Institute of Pathology revealed that during the Operation Iraqi Freedom, multiple casualties were caused by lethal penetrating injury in the thoracic region [3]. Of these lethal penetrating injuries 32.9% occurred just outside of the area protected by a ballistic plate. Wound entries were observed above (12.3%), on the sides (15.1%), and below (5.5%) the plate, with 19% of the injuries occurring near the edge of the plate (i.e., 4% near the top edge, 12.3% near side edge, and 2.7% near the bottom edge). Only 6.8% of the injuries observed were in the plated area. Similar observations were made in Ukraine, where the incidence of penetrating thoracic trauma outside of the protected region is significantly higher than in other conflicts [4]. Thus, there might be opportunities to further optimize the shape and dimensions of individual ballistic protection.

Designing an optimal ballistic plate is not a simple task since compromises must be made between the protection it offers (i.e., the ability to stop a threat and protect organs from life-threatening injuries) and the physical burden it adds to the soldier. In most research, fit and comfort are typically assessed separately from coverage protection performance. Studies on fit and comfort are usually done on soldiers wearing actual or prototype protective equipment. Such studies can help understand the effect of plate dimensions on the range of motion and operability offered by a protection system [5-7], but give little to no information on the actual protection provided by the equipment. Fit studies can also be performed with soft tissue simulation tools where pressure points and air gap can be correlated to the level of fit and comfort [8]. Studies on coverage protection are more commonly performed through Vulnerability and Lethality (V/L) analysis where an anatomical model that corresponds to the anatomy of a single individual is used to assess potential injuries sustained by soldiers struck by a projectile. Such study helps to understand the vulnerabilities of the human body when impacted by ballistic projectiles and to identify critical regions that require protection [9-12]. Analysis of protection coverage using Computerized Tomography (CT) scans and organ positions can also provide information on the effect of stature and morphology, but this information can be difficult to relate to generic V/L model anatomy [13-15]. Because mobility and comfort metrics are naturally different from vulnerability metrics, it is difficult to

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define a mobility-vulnerability trade space to optimize ballistic protection. To optimize ballistic protection, a robust methodology to study coverage performance, fit and comfort must be developed. The aim of the current study was to inform such design optimization process by evaluating the impact of changes in ballistic plate geometry on its ability to minimize the risk of life-threatening injuries. A methodology to assess coverage performance is presented where the Canadian Operational Research Environment for Vulnerability and Lethality (CORE V/L) software was used in conjunction with various protection performance metrics (i.e., Average Anatomical Profile (AP) Score, Average New Injury Severity Score (NISS), Average Injury Severity Score (ISS), etc.) to evaluate parametrically the effect of changes in the length and width of a plate. A range of ballistic plate configurations were therefore simulated against relevant threat and compared in a way that can inform designers of the effect of small geometric changes on protective performances.

2 METHODOLOGY

All analysis was performed using the CORE V/L tool. This software allows the prediction of injuries from projectile impact on a dismounted combatant. The anatomical model can be equipped with Personal Protection Equipment (PPE), and the effect of PPE on projectile performance can also be evaluated. Different types of simulation can be performed with the software depending on the objective of the study. For the current study, the relative performance of various PPE design was investigated. Different models and methods are needed to perform this type of analysis.

2.1 Anatomical Model and Injury Prediction

To model the effect of projectiles on the human body, an anatomical model of the human male is used. The model is composed of approximately 2500 structures divided into seven subgroups: circulatory system, connective tissue, lymphatic system, muscle, nervous system, organ, and skeleton. Figure 1 shows the CORE V/L male avatar in a standing pose with its different subgroups (i.e., skin and protection, organs and circulatory system, and skeleton). For simplicity, all simulations were conducted with the anatomical model in a standing posture. To help with the comparison of the coverage offered by different ballistic protection to the thoracic region of the human body, anthropometric measurements were collected on the model according to measurement locations presented in ANSUR II and CFAS anthropometric survey [16, 17]. Measurements were specific to the thoracic region. Anatomical land mark (i.e., Suprasternale notch (A), chest point (B), tenth rib (C), and iliac crest (D)) and measurements are illustrated on Figure 2, and the corresponding values for the anatomical model are presented in Table 1.

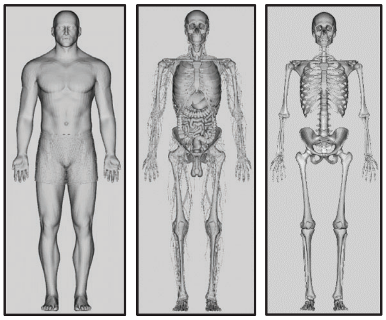

Figure 1. CORE V/L anatomical model of the human male.

From these measurements, a representative reference area of the thoracic region can be computed. This region represents the ideal medical coverage proposed by Breeze [12], spanning from the suprasternal notch to the iliac crest in length, with the chest breadth at the top and the bicristal breadth at the bottom. The reference area can be computed with Equation (1), and the representative surface is presented in Figure 2. For the anatomical model, the reference area is 1104 cm^2.

$$A_{ref} = \frac{(M_3 + M_4)}{2} M_2 \qquad \textbf{(1)}$$

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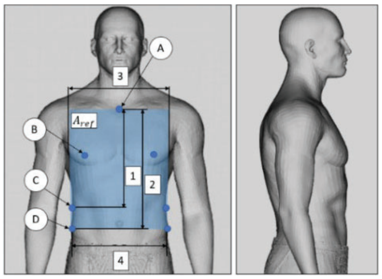

Figure 2. Identification of landmarks and measurements on the anatomical model.

Table 1: Anthropometric measurements for CORE V/L anatomical model.

ID	Measurement	Values (m)
1	Suprasternale-Tenth Rib Length	0.311
2	Suprasternale-Iliocristale Length	0.384
3	Chest Breadth	0.299
4	Bicristal Breadth	0.276

2.2 Ballistic plate

To evaluate the effect of length and width on coverage performance, multiple ballistic plate geometries were generated using a custom model generator in the CORE V/L toolkit. For this study, the general shape of the plate was inspired by the medium SAPI size, and only the width and length of the ballistic plates were modified between geometries. Dimensions of the different plate geometries were defined relative to a reference length measurement (i.e., Suprasternale-Tenth Rib Length), and a reference width measurement (i.e., Chest Breadth). The length of the plate varied from 120% to 60% of the reference, and the width varied from 100% to 40%. For this study, 49 permutations of the plate geometry were generated and analyzed. Figure 3 shows all the plates and their fit on the anatomical model. All plates were centred on the torso, fitted to the body, and the top edge was aligned with the suprasternal notch.

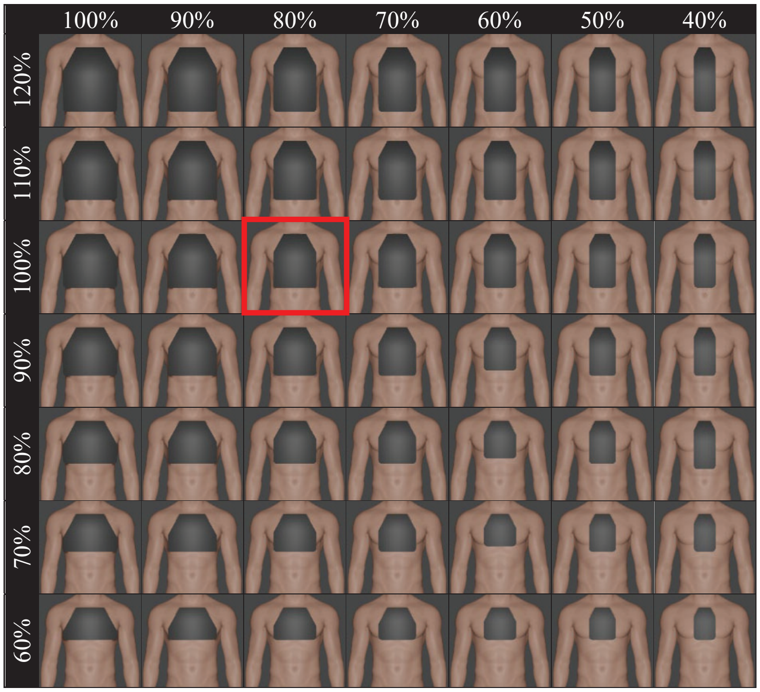

Figure 3. Placement and geometry of all 49 ballistic protections on the anatomical model. Relative dimension of the medium SAPI size is identified with a red rectangle.

A medium SAPI size was also simulated since it is the standard plate size that fit the anatomical model. The relative size of the medium plate corresponds to approximately 100% of the reference length and around 80% of the reference width. Since a coverage performance analysis of the various plate geometries is performed for this study, interaction between projectiles and the ballistic protection are not considered. Once an impact with the plate geometry is detected, the projectile is considered blocked. Also, to normalize result based on body shape and size, the coverage of ballistic protections normalized by the anatomical model reference area (Eq. (2)).

$$Relative\ Coverage\ Area = \frac{A_{plate}}{A_{ref}} \quad \textbf{(2)}$$

2.3 Projectile model

To assess the performance of ballistic protections, two relevant projectiles were chosen (i.e., 5.56 mm and 7.62 mm). The two projectiles were modelled based on generic properties and do not necessarily represent a specific threat. Mass (m), density (ρ_p), shape factor (γ), and impact velocity (v_s) are presented in Table 2. To simplify the modelling process, tumbling, degradation, and deviation of the projectile after impact are not modelled. Retardation of the projectile and damage tissue volume along the shot line are modelled using a penetration model adapted and upgraded from the Computer MAN model [18].

Table 2. Projectiles properties.

Projectile	Mass (gr)	Density (kg/m^3)	Shape Factor (-)	Impact Velocity (m/s)	Kinetic Energy (kJ)
5.56 mm	62	8960	0.360	950	1.813
7.62 mm	154	8960	0.406	850	3.605

To assess coverage performance, multiple independent shot lines were fired at the CORE V/L anatomical model. For each engagement orientation, 3600 shot lines were modelled, and distributed on a uniform equidistant grid with 10 mm spacing. Three azimuth angles were chosen to assess the coverage performance (i.e., Az. -45°, 0°, and 45°). The location of all shot lines can be observed on Figure 4. Each dot corresponds to the starting point of a shot line, and their directions are perpendicular to the corresponding grid.

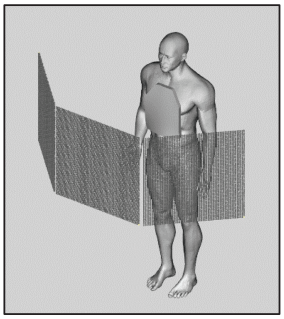

Figure 4. Shot line location and orientation fired at the anatomical model.

2.4 Injury Prediction and Coverage Performance Metric

To assess injuries caused by projectiles, CORE V/L correlate tissue damage evaluated by the penetration model to anatomical based injury description from the Abbreviated Injury Scale (AIS) 2015 revision [19]. For each shot line, multiple injury descriptions are recorded and a severity score is assigned to each one. Severity score for injuries varies from minor (AIS 1) to maximal (AIS 6). From the injury assessment different scoring methodologies can be used to assess the likelihood that a soldier will survive the injury cause by a projectile. The three scoring methodologies tested for this study are the Injury Severity Scale (ISS) [20], the New Injury Severity Scale (NISS) [21], and the Anatomical Profile (AP) [22]. Those survivability metrics compute a probability to survive (P_s) based on the injury descriptions related to a shot line.

To attribute a unique score for each ballistic protection tested, an average P_s ($\overline{P_s}$) can be computed over all shot lines. However, since ballistic protections are meant to protect the thoracic region, only shot line that causes injuries in that region will be used to compute the average score. The exclusion of shot lines in the averaging process will be performed based on the AIS region related to the maximum AIS (MAIS) injury description over that shot line. The AIS body regions that are included in the computation are presented in Table 3. The resulting $\overline{P_s}$ score will be used in this study to rank the coverage performance offered by each configuration tested.

Table 3. Specific AIS regions included in the $\boldsymbol{\overline{P_s}}$ computation.

AIS Code	Region
4XXXXX.X	Thorax
5XXXXX.X	Abdomen
6X04XX.X	Spine - Thoracic
6X06XX.X	Spine - Lumbar

3 RESULTS

From the terminal ballistic simulations, injury assessment of 10,800 shot lines in three different orientations was performed. Figure 5 presents an example of the data generated for an unprotected and protected soldier. Results are presented according to the MAIS severity measured for a particular shot line. It can be observed that for this ballistic protection (i.e., Medium SAPI), all maximal injuries are being protected from frontal engagement, and most critical injuries in the upper thoracic region are also being protected. However, for engagements with azimuth angles varying from -45° to 45° more critical and some maximal injury severities are being exposed. This supports the importance of assessing different engagement angles to evaluate coverage performance of ballistic protection. With results from each independent shot line, severity metrics can also be computed. Figure 6 present result for all severity metrics (i.e., AP, ISS, NISS) in the Az. 0° orientation. It can be observed that all severity metrics behave differently. The distribution of ISS metric seems to match with the distribution of maximal and some critical severity regions, which is not the case for NISS and AP. The NISS, and AP do not necessarily match MAIS metric, but seem to represent a cumulative effect of all injuries caused by the projectile. It can also be observed that for the NISS and AP the lowest probability of surviving an injury is located at the midline of the body.

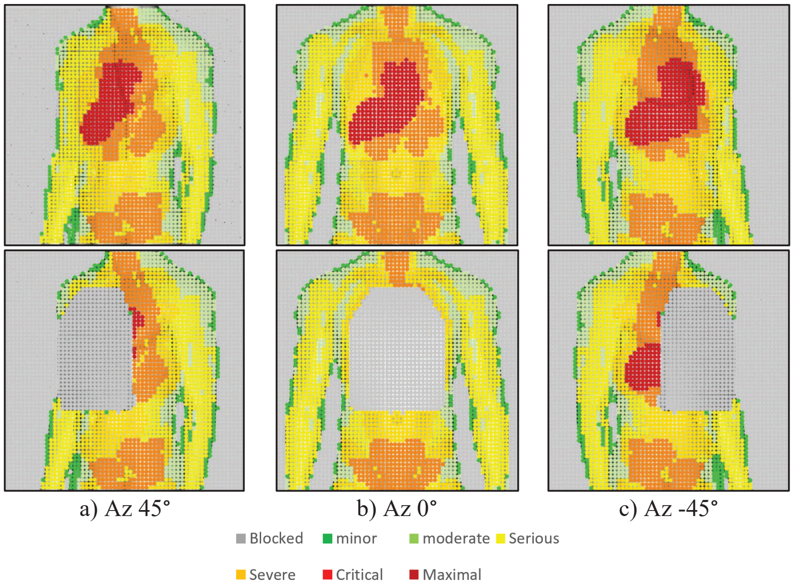
a) Az 45° b) Az 0° c) Az -45°

Figure 5. Protected and unprotected simulation result for Az. 45°, 0°, and -45°.

From the results presented in Figure 6, the computation of $\overline{P_s}$ was performed for each configuration tested and each survivability metrics. Those results are presented in Figure 7. It can be observed that all injury scoring systems give different results for a same configuration. For example, the average probability of surviving for an unprotected soldier impacted by a 5.56 mm projectile is 0.39 with the AP score, 0.50 with the NISS score, and 0.73 with the ISS score. The offset seems to stay relatively constant between NISS and AP results, but it is not the case between the ISS and AP. In that scenario, the offset between the two scoring methods reduces as the relative coverage area increases. Furthermore, the behaviour between the scoring system seems to stay consistent when two projectiles of different masses and impact velocity are used. However, the use of the heavier projectile systematically resulted in lower average protection performance metrics. Result from Figure 7 also shows a good correlation between the probability to survive an injury and the relative coverage area. This correlation is most significant for the AP score as there is less dispersion than with the other metrics. This also indicates that changes in length or width alone may not have a significant influence on survivability scores. Given that the AP score demonstrated the highest sensitivity among the other metrics, all subsequent results will rely exclusively on this metric to assess coverage performance of ballistic protection.

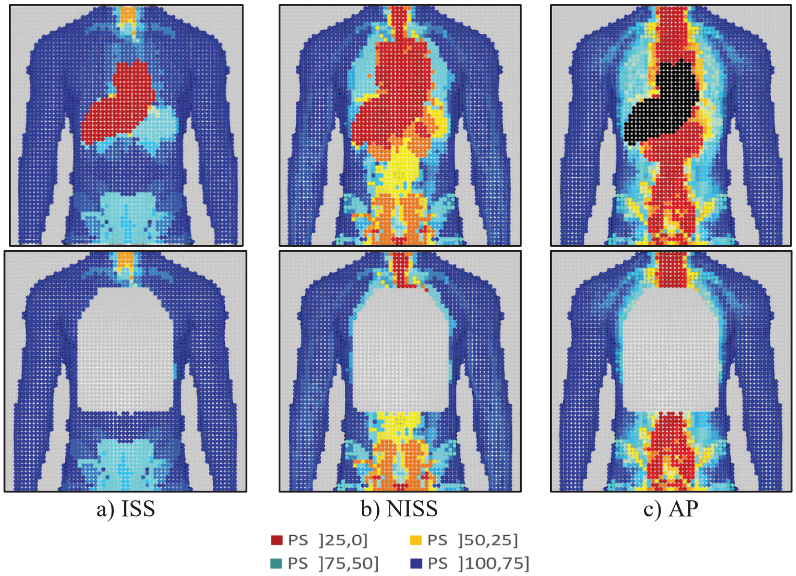
a) ISS b) NISS c) AP

Figure 6. Protected and unprotected simulation results for three survivability metrics.

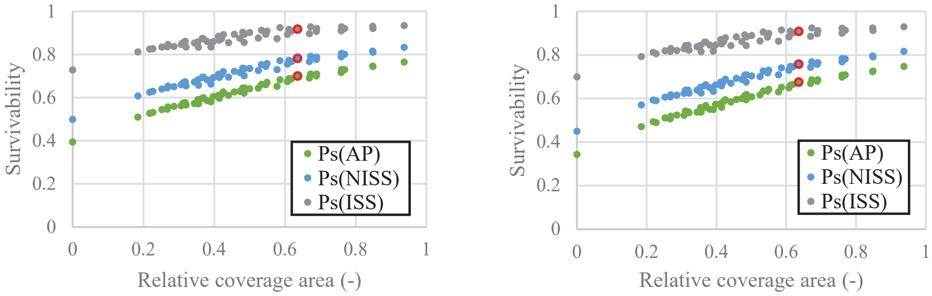
a) 5.56 mm b) 7.62 mm

Figure 7. Average probability to survive injuries over relative coverage area based on all configurations tested. The red circle indicates the medium SAPI size result.

To better understand the relationship between length, width, and coverage area an isosurface plot was computed. From Figure 8, isolines correspond to a change in relative coverage, whereas colour gradient corresponds to change in $\overline{P}_s$. From the results, it can be observed that for a specific relative coverage area, there exist a combination of length and width that maximize the survivability metric. Linear interpolation was performed between all the results to find those optimized combination for the isolines presented in Figure 8. Optimized configurations are identified with red dots on Figure 8 and the specific values are presented in Table 4. From those results, it can be observed that for both projectiles larger plates seem to maximize the $\overline{P}_s$, when the full width is used. However, for smaller plates an equal proportion of length and width seem to maximize the $\overline{P}_s$. It can also be observed that changes in plate length and width have a relatively minor effect on the $\overline{P}_s$, as the range between minimum and maximum values for a specified relative coverage is considerably smaller than the variation in the coverage performance metrics across different coverage areas.

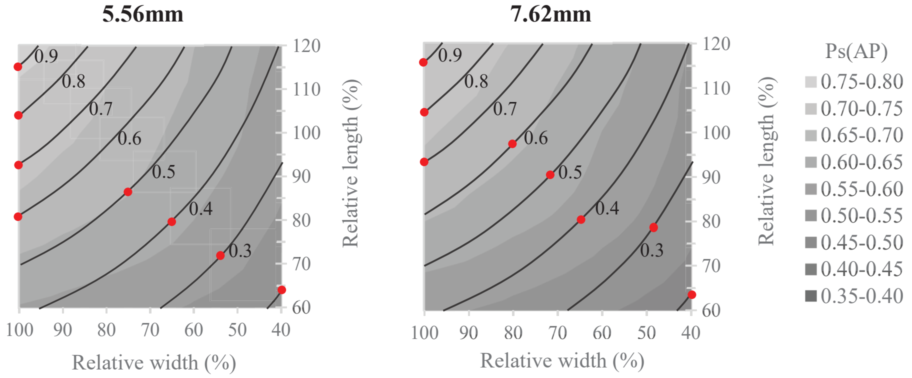

Figure 8. Average probability (i.e., AP) to survive injuries over the relative dimensions of the plate (i.e., length, and width) for all configurations tested. Relative coverage area is presented with iso lines, and the colour gradient represents the probability of surviving injuries. Optimized interpolated configurations are presented with red dots on the iso lines.

Table 4. Min and max $\overline{\boldsymbol{P}}_{\boldsymbol{s}}$ for a given relative coverage area.

Rel. Coverage	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
5.56mm								
Max $\overline{P}_s$	0.7560	0.7289	0.6995	0.6604	0.6257	0.5841	0.5582	0.5171
Min $\overline{P}_s$	0.7565	0.7362	0.7144	0.6856	0.6515	0.6140	0.5685	0.5175
7.62mm								
Max $\overline{P}_s$	0.7373	0.7098	0.6775	0.6385	0.5990	0.5525	0.5192	0.4768
Min $\overline{P}_s$	0.7380	0.7147	0.6910	0.6575	0.6233	0.5813	0.5359	0.4802

4 DISCUSSION

4.1 Effectiveness of survivability metrics and relative coverage area to quantify ballistic protection's coverage

This study introduced novel metrics that quantitatively characterize the performance of different protection systems, demonstrating their potential as effective tools for comparative evaluation. The average probability to survive ($\overline{P}_s$) was computed for three injury scores (i.e., ISS, NISS, and AP). Significant differences were observed as presented in Figure 7, with the most significant differences being observed between the ISS and the two other metrics. This difference can be explained by the use of three MAIS severities identified for a given shot line to assess the survivability of soldiers. Another limitation is that the three severities used must be from different body regions. Since penetration of projectiles usually cause injuries in a single body region, it was observed that outcomes were underestimated. Those limitations of the ISS metric were also reported in other studies [23, 24]. The other two metrics (i.e., NISS, and AP) are not limited by body regions thus allow for a better representation of every injury identified for a given shot line. The AP metric being a more complex method, that includes all injuries from a given shot line seem to significantly predict lower survivability than the simpler NISS metric, which indicates that the AP is more sensitive. For this reason, the AP metric was chosen for most results presented in this study.

To quantify the coverage of ballistic protection, a relative coverage area was computed. This metric is a measure of the area ratio between the ideal medical coverage and the surface of ballistic protection. However, this metric does not necessarily consider the additional protection provided by a curved plate for angled shots. To demonstrate the correlation between the ability of a protection to stop projectiles in the thoracic region and the relative coverage area metric, the percentage of projectiles successfully stopped was recorded and presented in Figure 9. Results indicated that the relative coverage area of a plate is generally a reliable predictor of the number of blocked shot lines. However, this relationship weakens for a protection system that has larger coverage. This indicates that for larger plates, a more pronounced curvature has a larger effect on the ability of a protection system to block projectiles.

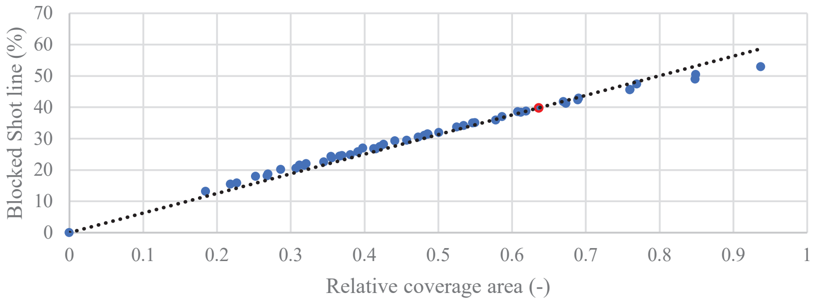

Figure 9. Correlation between relative coverage area and the ability to block shot lines in the thoracic region.

4.2 Effect of Ammunition Properties on the Coverage Performance of Ballistic Protection

In the current study, the coverage performance of 49 ballistic protections was assessed with two relevant projectiles (i.e., 5.56 mm, and 7.62 mm). The data generated by CORE V/L and presented in Figure 7 and Figure 8 shows differences between the projectiles tested. By comparing results obtained with the AP metric in Figure 10, it can be observed that the larger projectile present significantly lower $\overline{P_s}$. This is due to the larger projectile having more kinetic energy at the impact than the other one. Since damage caused to live tissue is most often proportional to the energy deposited by the projectile, it is to be expected that the larger projectile will cause more damage resulting in lower average probability to survive.

It can also be observed from Figure 10 that the difference in $\overline{P_s}$ between the two projectiles reduces as the relative coverage area increase. Similar differences also seem to be observed in Figure 8, where the behaviour of the optimal configuration changes at a relative coverage area of 0.6 for the 7.62 mm as opposed to 0.5 for the 5.56 mm projectile. Further investigation is required to fully understand the differences observed between the two projectiles as the coverage increase. However, preliminary analysis suggests that projectile size, shape and kinetic energy all contribute to the observed variations in the data.

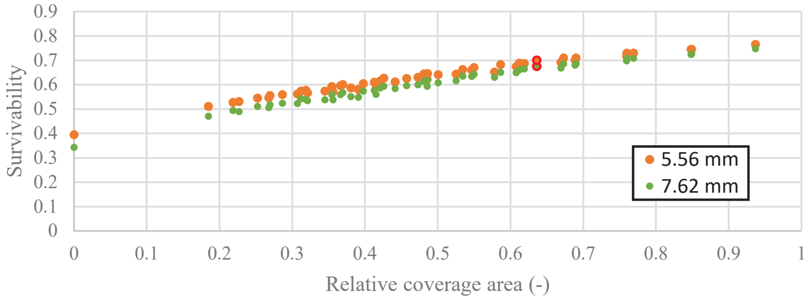

Figure 10. Effect of projectile properties on the $\overline{P_s}$ metric.

4.3 Extending results to military personnel

In an attempt to extrapolate the generated data to a larger military population, plate dimension, and coverage area were normalized based on CORE V/L anatomical model anthropometry. Length has been normalized by the suprasternal to 10th rib length; width has been normalized by the chest breadth; coverage area has been normalized by the reference area of the thoracic region. Thus, by comparing anthropometric measurements taken on a soldier and the size of a plate, one would be able to assess the coverage performance of a specific plate on an individual. It would also be possible to estimate the gain or decrement in coverage performances if a larger or smaller plate size is being used. By interpolating between results and extending those results to a larger population, a linear scaling assumption would need to be made. This would indicate that organ size and placement are assumed to scale linearly based on external anthropometric landmark. However, there is evidence in the literature that organ location may not correlate to external body markers [15, 25, 26], and there also exist significant difference between male and female anatomy that would need to be taken into consideration. More investigation would be needed to better understand the effect of stature, gender, and organ location on the coverage performance of ballistic protection.

The current study also proposed that an optimization of the length and width of a ballistic protection can be performed for a given relative coverage area in order to maximize the $\overline{P_s}$ metric. However, other factors would also need to be considered to optimize the geometry of a ballistic protection for the threat and environment that soldiers are exposed to. For example, fit and comfort, weight, and thermal load are other factors that play an important role in this optimization of protection system. To evaluate the interaction between those parameters, genetic or other AI algorithm could help in that process. There exist studies, like the one presented by Khoe, where a soft tissue protection was optimized based on V/L analysis, thermal loading, and weight [27]. However, no study presented in the literature was found to optimize protection system based on all factors.

5 CONCLUSION

This study used the CORE V/L tool set to assess the effect of length, width, and coverage area on the coverage performances of ballistic protections. The analysis was performed on a series of 49 ballistic plate models, with varying length and width. Plate dimensions were all referenced to anthropometric measurements of the thoracic region. Simulation of the impact of 10,800 independent projectiles oriented in three different directions was performed with two distinct projectiles (i.e., 7.62 mm and 5.56 mm). Injury prediction and survivability metrics (i.e., ISS, NISS, AP) were assessed on each shot line. From that assessment, an average probability to survive ($\overline{P_s}$) was computed, which allowed ballistic protection to be ranked based on their shape and size. From those results, survivability metrics were found to perform differently, with the ISS presenting large differences compared to the others, and the AP presenting the most sensitivity to injuries identified for each shot line. Differences were also observed between the two projectiles simulated as size, shape and kinetic energy seem to influence damage caused to the tissues model. By comparing the effect of length, width and coverage area, it was found that the coverage area has a larger influence on the $\overline{P_s}$ compared to length and width alone. However, it was also found that for a given coverage area a combination of length and width can be found to further optimize the coverage performance. The methodology presented in this paper allowed for a ranking of different ballistic plate shapes and sizes to be made and inform how relative changes to the plate can influence the risk of life-threatening injuries. Since plate dimensions are referenced to anthropometric measurements on the anatomical model, it would be possible to extend those results to a military population and estimate the gain or loss in coverage performance offered by ballistic protection to an individual. However, this presents some limitations as differences in organ placement, stature, and gender are not taken into account. Subsequently, to optimize the geometry of a ballistic protection, other factors also need to be considered, like fit and comfort, weight, and thermal load. A potential way forward could be the development of a genetic or another AI algorithm that would optimize plate geometry based on V/L model to assess coverage performances, soft tissue models to assess fit and comfort, and other loading models that would affect the operational capability and survivability of a soldier.

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