Document Title: Characterization of Weapons used in Stab/Slash Attacks

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Abstract

This report is submitted in conjunction with Biokinetics '*Characterization of Weapons Used in Stab Attacks – Surrogate Development Final Report*' and details the work completed by Wayne State University (WSU) in reference to a National Institute of Justice (NIJ) Program entitled 'Characterization of Weapons used in Stab/Slash Attacks'. Whereby, WSU was contracted by the National Institute of Justice to provide scientific support and guidance to a newly formed Special Technical Committee (STC), whose overall goal was to review and revise the current NIJ standard 0115.00 *Stab Resistance of Personal Body Armor*, to ensure that it accurately addresses the requirements of its current end user.

The work in this contract was divided into several phases, summarized as follows:

Phase 1, Part A – Survey of Weapons: Correctional and law enforcement agencies across the United States were requested to provide any and all sharp edged weapons that were confiscated over the last few years. Over 1300 weapons from twenty (20) states were collected in this process.

Phase 1, Part B – Weapon Typology: All the weapons received were logged, photographed and had specific measurements determined based on a typology database nomenclature developed in conjunction with Biokinetics.

Phase 2 – Weapon Typology/Improvised Weapon Exemplar Development: Biokinetics finalized the typology for the improvised weapon exemplars, using the knowledge gained in Phase 1 by WSU and from an approach that involved the key components of how delivery occurs and the armor interaction with the weapon. The goal was to have specific classifications based on threat to life. Performance based taxonomy of the surveyed weapons included tip and edge sharpness, weapon hardness and push-through tests. The weapons were down-selected and an initial set of weapon exemplars was developed.

Phase 3 – Exemplar Weapon Comparison: The final phase of the program was to compare the relative performance of the new improvised weapon exemplars to the P1, S1, and Spike threats found in the NIJ 0115.0 Standard. Preliminary statistical analysis was performed to evaluate the newly developed exemplar(s) and their relative performance in relation to threat to life. Four exemplar weapons were developed to represent the threats found in correctional facilities and may be considered for future updates of relevant body armor performance standards such as NIJ 0115.00.

The following summarizes the results of this study: (1) a stab weapon typology and taxonomy were successfully developed to identify potentially aggressive threats based on descriptive information, (2) quasi-static performance tests were developed to characterize tip, edge and system performance for initial down-selection of stab weapons, (3) two bladed and two spiked exemplar weapons were developed from the geometric and performance characteristics of weapons obtained from correctional facilities in the US, (4) the proposed exemplars require a lesser number of armor layers to meet the current penetration limits of NIJ 0115.00 in comparison to the P1/A and S1/G exemplars, and (5) greater use of the exemplars from the practitioners is required to fully understand their implications on armor design, relevancy and test variability. Additional work is required to establish confidence levels and potential for quality control measures of the exemplars.

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R13-11 Char of Weapons Stab - Ph II

Executive Summary (Modified from Shewchenko et al., Appendix E)

ABSTRACT

Characterization of weapons found in correctional institutes within the United States previously had not yet been conducted. The performance standard for personnel protection was based on data collected outside of the US.. The present study describes the characterization of threats obtained from a large survey of correctional institutions in the United States and their simplification into exemplars for use in performance standards. An Analytic Hierarchy Process (AHP) was applied to the weapon survey data to create a weapon typology for subsequent down selection and detailed performance analysis. Test methodologies for tip sharpness, edge sharpness and weapon system performance were developed for initial characterization of the weapons and for validation of the exemplars. Dynamic tests on commercial armor systems consistent with the NIJ 0115.00 test methodology were conducted to assess the threat exemplar severity and implications on armor design. The study identified bladed and spiked threat classes found in correctional environments and led to the development of similar exemplar classes. The presence of both threats may require an integrated approach for the development of stab resistant armor. Findings from the study are being considered for revision of the NIJ 0115 standard for assessing the stab resistance of body armor.

INTRODUCTION

Approximately 13% of law enforcement officers in the United States were assaulted by knives or cutting instruments according to the 2009 Law Enforcement Officers Killed and Assaulted (LEOKA) report. While similar statistics are not collated at present, it is likely that similar concerns exist with spiked, bladed and improvised weapons found in the correctional environment. In addition, the types of weapons used, mode of use and effectiveness in defeating protective armor is not well characterized.

Current standards such as the NIJ 0115.00 *Stab Resistance of Personal Body Armor* [1] have been based on the use of commercial weapons in crimes within the civilian population. These weapons typically exhibit well-refined characteristics for optimal performance during puncturing, cutting and penetrating actions under controlled use. In comparison, weapons used in a corrections environment are less refined due to the limited access to materials, manufacturing capabilities, and need for concealment. It has been speculated that a lower level of performance would be exhibited by these improvised weapons placing less demand on stab resistant body armor.

The study is motivated by the current efforts of the Special Technical Committee (STC) operating under the NIJ to re-address stab and slash threats in the US and revise the NIJ 0115.00 standard accordingly. The STC operates under two oversight groups appointed by the NIJ: the Advisory Working Group (AWG) and the Standards Steering Committee (SSC). The work is taking place as part of the overall efforts of the STC to address the test methodology, armor certification process and provide guidance to key decision makers and equipment users. Contributions and oversight from the practitioners (law enforcement, corrections, criminal justice subject matter experts and end users) and technical experts (representatives from federal agencies, academia, and private industry including scientists, engineers and laboratory personnel) are intended to ensure that the needs and requirements of practitioners in the field are addressed.

This study aims to answer a knowledge gap identified by the STC in regards to stab weapon performance in the corrections environment. Characterization and assimilation of the weapons was conducted with the objective of producing revised weapon exemplars representative of correctional threats.

WEAPON SURVEY

In 2010, NIJ initiated a research program to identify the threats experienced by law enforcement and corrections officers which operate inside controlled access facilities, including jails, detention centers, and prisons or outside the facility to control access. The threats of concern inside the facility include stab threats, slash threats and blunt impact threats while outside the facility ballistic threats are prominent. Only stab threats are addressed in the present study and will be the focus of subsequent discussions.

Stab threats made by inmates tend to be improvised from available materials (*e.g.* metal, plastic, wood) and administered from the back of the officer or in close quarters with the officer knocked down and the weapon used in short jabs against the torso. Typical correctional stab type weapons are found in Figure 1 and include blades, spikes, shivs, and stakes. Commercial weapons are rarely found due to the difficulty in importing these into the facility.

Figure 1: Typical improvised weapons found in correctional institutes.

Wayne State University was tasked by the NIJ to provide scientific support for characterizing inmate-manufactured or improvised weapons that a correctional officer faces in the United States. The first step was to procure confiscated improvised weapons from correctional facilities across the US and create a typology where the weapon attributes such as size, shape and sharpness are documented.

A total of 1353 weapons were collected from over 20 facilities representing different prison types and security levels. The weapons were subsequently photographed, measured and entered into a weapons database. The weapons were initially classified into four styles as provided in

Table **1** with the distribution of styles presented in Figure 2.

Table 1: Definition of weapon types collected in the survey.

Weapon Style	Description
Blade	Flat blade with rectangular cross section generally having a tip, edge and handle. To be used in a thrust mode and possible drag/slash follow-through.
Ice Pick	A typically round shaft construction having a tip, slender shaft and handle. To be used in a thrust mode.
Stake	Similar to the blade but with an irregular cross section.
Slash	A small flat blade generally without a tip but having a supporting handle. The blade may be oriented perpendicular to the handle. To be primarily used in a slashing or sweeping mode.

WEAPON TYPOLOGY

Development of a weapon typology must account for the dynamic performance of the weapon and trauma inflicted to the victim. Consideration must be given to the assailant delivering the weapon, the interactions of the weapon with the armor, and the bodily response to the assault. For completeness, the impact of the weapon and potential for injury should also account for the dose-response relationship, exposure assessment and risk characteristics. However, due to the paucity of literature on stab attacks, a more simplistic approach is required to meet the current programs' objective of weapon characterization and exemplar development. Emphasis was, therefore, placed on characterizing the physical and geometric attributes of stab weapons found in correctional environments as well as assessing their performance against armor systems.

In regards to stab/slash attacks research studies have discussed the weapon attributes in relation to human injury and armor failure [2, 3, 4, 5, 6, 7, 8]. Terms such as tip sharpness, edge sharpness, body slimness/shape, surface finish and material have been referenced and associated with the weapon's performance. A quantitative understanding of a weapon performance attributes can be gained from an engineering study of cutting tools by Atkins who describes the primary modes of action including piercing, cutting, parting/wedging, and sawing [Atkins 2009]. These actions are related to physical attributes of the weapon such as the tip and edge, including their approach angle, tip radius, included cone angle, among others.

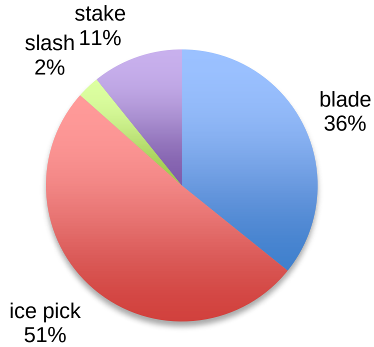


Figure 2: Distribution of weapon type from the survey.

Based on the literature, an initial typology was established to document the physical weapon attributes responsible for penetration (tip and edge sharpness, surface finish, slimness, etc.) along with information on its intended method of use. A detailed description of typical parameters was created and later simplified for use in the ranking process as provided in Table 2.

The typology effort and implementation of a weapon database was carried out in a stepwise approach to cope with the large amount of weapons from the survey. Three levels of activity were planned; Level I - was intended to document rudimentary geometric data and qualitative descriptions so that a subset of aggressive weapons could be identified; Level II - was to provide detailed geometric and quasi-static performance measurements for the subset of aggressive weapons, and; Level III – provided performance data and analytical data for exemplar development.

The processes used to accomplish the taxonomy and exemplar development effort are illustrated in Figure 3 with the first tier encompassing the typology or descriptive information about the weapons. The ranking process in the second tier is intended to assign a weapon performance score based solely on the typology. This information is subsequently used in the third tier to reduce the sample size making more detailed performance assessments manageable within the scope of the program. The performance assessments in the fourth tier are intended to assess tip and edge sharpness with quasi-static tests in lieu of geometric data which was not practical to measure. The fifth tier attempts to consolidate the performance results to help guide the development of exemplar weapons.

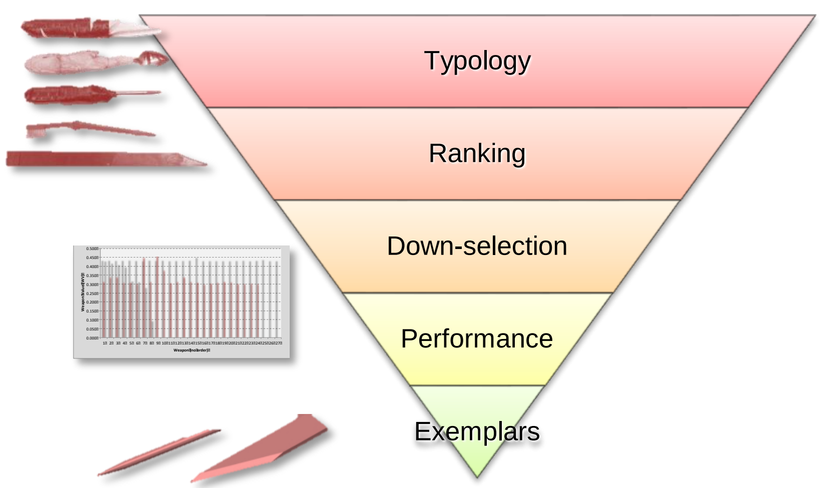


Figure 3: Exemplar weapon development process.

WEAPON TAXONOMY AND RANKING

Weapon performance ranking is ideally based on empirical relationships between weapon typology and performance for all weapons. However, due to the lack of available weapons for empirical investigations and availability of descriptive attributes (*i.e.* geometry, materials, intended mode of use) a weapon performance assessment method is required based solely on the attributes. Further challenges are present with the wide variety of data forms among the attributes including textual, numerical and ordinal types.

To realize a taxonomy scheme, a Multiple Criteria Decision Making (MCDM) process was used to consolidate and rank the weapon information. In principle, a weighted objective function is defined based on fundamental weapon attributes that contribute to its performance. It is of the form:

$$Objective = \sum_{i=1}^{n} W_i(C_i) \tag{1}$$

where:
C = the objective criteria, W = the weighting factor, n = the number of criteria.

Each criteria is prioritized in accordance to their relative contribution to performance. The sum of all the prioritized criteria then reflects the overall performance of the weapon. When completed for each weapon, the values can be ranked and grouped to identify those with the propensity to perform more effectively. It is recognized that this is an approximation of the weapons true performance but until experimentation can be conducted with a small set of down selected weapons, this is considered a viable means to classify the weapons.

Establishing the priorities or weighting factors for the criteria based solely on descriptive information is problematic as qualitative and quantitative information is used. To address this, a subset of the MCDM process called the Analytic Hierarchy Process (AHP) was used [9]. The AHP allows for consistent ranking of seemingly disparate criteria. It involves creating relative linear or non-linear rankings of paired criteria comparisons while providing an assessment of consistency between the rankings. Further, it can be applied to multilevel hierarchic structures where multiple objective functions are used, typically from low level to more global assessments.

Table 2: Weapon system level ranking and contributions.

Description	Function	Attributes	Comments
Attribute Level:			
Tip Feature	Perforation	Tip Material	Materials ranked by compressive modulus.
		Tip Cone	Sharper angles increase penetrability of weapon.
		Tip Width, Dia.	Related to cone angle.
		Tip Length	Related to cone angle and max. penetration possible.
Edge Feature	Cutting	No. Edges	Greater number promotes cutting and penetration.
		Edge Condition	Sharper edges promotes cutting or separation.
		Edge Material	See tip material.
Blade Feature	Force delivery	Blade Width	Larger x-section allows greater effort and integrity.
		Spike Dia.	As above.
		Blade Material	Stronger materials more capable of higher loads.
		Weapon Length	Length effects buckling and stability.
		Handle Length	Effects retention of weapon and load transfer.
System Level:			
Tip	Penetrability	Tip Value	AHP method of determination.
Edge		Edge Value	AHP method of determination.
Blade		Blade Value	AHP method of determination.

The structure of the weapon data for the AHP criteria used in the study is presented in Table 2 having similar attributes to those identified in the literature. The attribute level AHP, such as the effectiveness of the tip, is based on the weighted contributions of the tip perforation performance, which in turn is based on the weighted contributions of material, cone angle, diameter/thickness and length. In comparison, the system level AHP criteria take into account the combined weighted contributions from the tip, edge and blade of the weapon.

The hierarchical process is applied to the tip, edge and blade as shown in Figure 4 where the criteria are identified as Tip Value (TV), Blade Value (BV), and Edge Value (EV). The criteria are defined below but are noted to use information directly from the topology database and from computed performance estimates. The weighting factors are denoted by the lower case letters, which are determined for each application level of the AHP.

Weapon Value $WV = a(TV) + b(BV) + c(EV)$ (2)

where:

WV = the system level assessment of the weapon performance,
TV = Tip Value, performance assessment of the tip,
BV = Blade Value, performance assessment of the blade,
EV = Edge Value, performance assessment of the edge, and;
a, b, a = weighting factors determined from the AHP.

The weighting values are determined through the AHP where expert opinion is provided in terms of relative weightings between matched pairs of criteria. For the Weapon Value, the weightings are provided in Table 3 which indicates that the tip value criteria has the greatest contribution to weapon performance followed by the blade and edge. Total weighting are normalized to a value of one by way of the AHP.

Table 3: Weapon Value weightings.

Criteria	Weightings	
TV - Tip Value	a	0.78
EV - Edge Value	b	0.07
BV - Blade Value	c	0.15
	Total	1.00

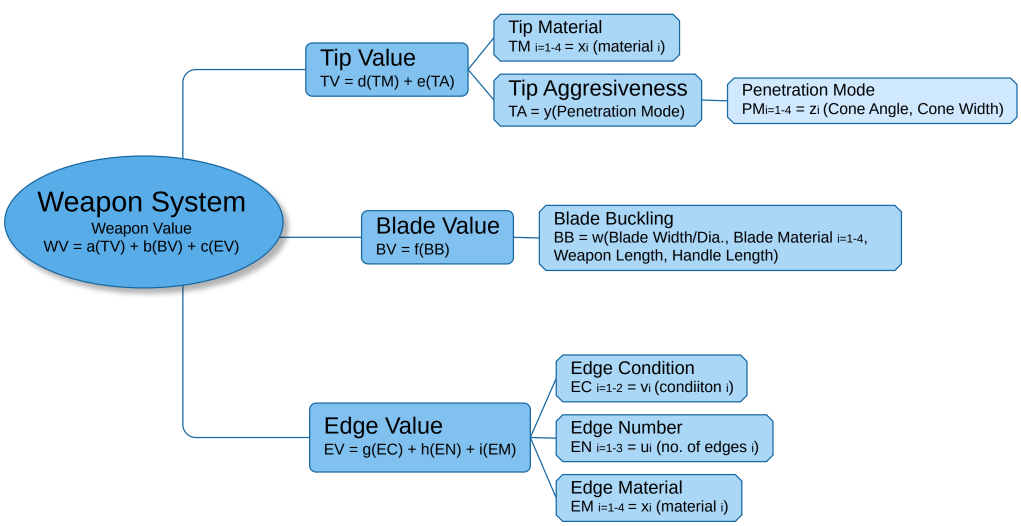


Figure 4: Hierarchal structure of the weighted weapon performance assessment function.

For the Tip Value, there were four calculated modes of penetration depending on the geometry of the weapon. For pointed weapons, the mode of penetration was assumed to be one of fibre separation and the cross-sectional area of the weapon presented at maximum allowable penetration was used to relate to the resisting forces. For blunt tips, a shear failure mode was assumed and the width or diameter is ranked to relate to the number of fibres involved in shear failure. In all cases, frictional forces and dynamic effects are ignored due to the lack of data in the initial typology. The Tip Value parameters are provided in Equation (3) and a topographical depiction is presented in Figure 5.

The AHP process was used to develop an overall ranking of the weapons performance as a system including the contributions from the tip, edge and blade. A sample of the Weapon Value for the bladed survey weapons is presented in Figure 6 showing the relative contributions of each attribute. A high Weapon Value predicts an aggressive weapon in terms of its penetrability. It should be noted that many rankings are based on coarse qualitative descriptions of the weapons and, as a result, the rankings are equally coarse but provide sufficient specificity to identify marginally performing weapons.

Tip Value TV = D*d(TM) + E*e(TA)	TV = Tip Value, performance of the tip, TM = Tip Material, performance of the tip material, TA = Tip Aggressiveness, performance of the tip geometry, d, e = weightings for TM (0.04-0.58) and TA (0.06-.53), D, E = weightings for TM (0.5) and TA (0.5).	(3)
Blade Value BV = F*f(BB)	BV = Blade Value, performance of the blade, BB = Blade Buckling, normalized buckling performance, F, f = weighting factors for the BB assessment (0.0-1.0).	(4)
Edge Value EV = G*g(EC) + H*h(EN) + I*i(EM)	EV = Edge Value, performance of the edge, EC = Edge Condition, the qualitative sharpness of the edge, EN = Edge Material, performance of the edge material, EM = Edeg Material, performance of the edge material, g, h, i = weighting factors g (0.17, 0.83), h (0.16-0.54), i (0.04-0.58) G, H, I = weighting factors for the relative importance of EC (0.26), EN (0.41), EM (0.33).	(5)

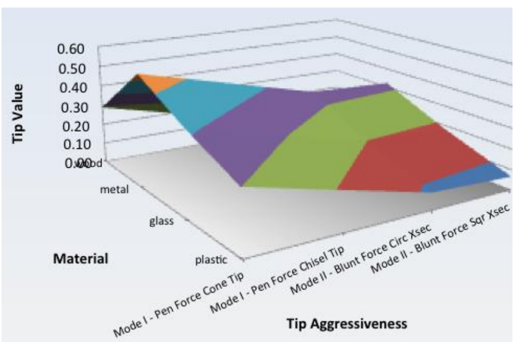


Figure 5: Tip Value topography based on weapon penetrability and material.

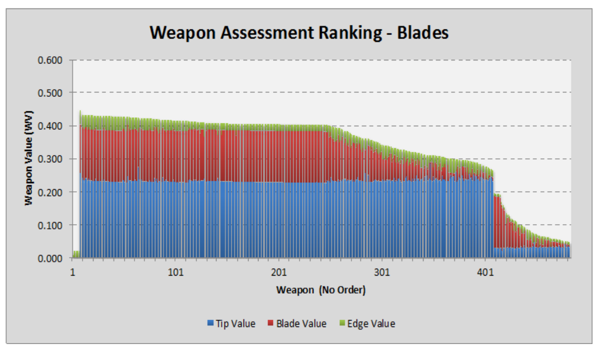


Figure 6: Weapon value rankings for bladed styles.

WEAPON DOWN-SELECTION

To reduce the number of weapons from the survey to a manageable amount for performance evaluations, a down-selection process was carried out by selecting the upper quintile of the Weapon Values for each weapon type (*i.e.* blade, spike, stake). In cases where there were insufficient weapons to meet the targeted sample size of 25 weapons, either the upper quartile was selected or lower ranking weapons were selected.

WEAPON PERFORMANCE ASSESSMENT

Upon completion of the down selection efforts, a higher degree of detail was required on weapon penetrative performance and geometry for development of the exemplars. Ideally, the geometric details of the weapon can also be used to characterize weapon performance such as the tip radius, tip cone angle, edge radius, edge profile, blade strength, blade stiffness and material strength. However, due to the imprecise manner in which the weapons were fabricated and the difficulty in obtaining extremely precise measures of radii and included angles, an alternate approach was used in which appropriate performance tests of the tip sharpness and edge sharpness were conducted. Additional tests included quasi-static armor push-through performance, blade hardness and flexural stiffness.

Tip Sharpness

The most current method for tip sharpness evaluation has been proposed in the HOSDB Spike and Knife Resistance standard [10] and adopted by the NIJ 0115.00 stab resistance standard. The methods rank the penetrating force required to indent a controlled material as a means to quantify sharpness and can be used as a relative ranking tool. In the current study, tip sharpness was assessed with a similar setup to NIJ 0115.00 where the indenter of a hardness machine was replaced with the tip of the weapon. The resisting force required to indent a block of pure lead 3 mm was measured. This provides constant interaction with the tip and was felt to better represent the interactions with armor systems. Further, the lead indentation block was selected in order to not damage the softer metals used in the improvised weapons.

Edge Sharpness

The edge sharpness test methodology was based on the principles developed by CATRA and proposed by Watson which measure the force required to press the edge of a weapon into a silicone rubber substrate [7]. For the current study, the force required to press the edge of the blade into a silicone strip of constant width at a given depth was measured. The tip was aligned with the front edge of the silicone rubber and the edge was parallel to the surface. The portion of blade edge interacting with the silicone was controlled by the width of the rubber strip. The rubber strip is wrapped around a rod to provide some surface tension as the edge cuts through the surface, thereby reducing interaction with the sides of the blade and reducing frictional effects, as intended by the CATRA test methods. The selected method provides an approximation of the edge sharpness as there are potentially different edge interactions with various armor materials (*i.e.* fabric, chainmail, metal/ceramic plates).

Blade Hardness

Knowledge of the weapon's blade material strength can be inferred from its hardness as this relates to the the yield strength. A standard Rockwell indenter test method was employed using the Rockwell "B" scale, being more appropriate for soft metals such as mild steel, aluminum and brass. Due to the small size of the indenter used, it provides local hardness measurements and is less susceptible to surface flatness deviations. The hardness test method employs a Rockwell tester to apply a standard preload to a 1.59 mm steel ball indenter followed by a major load (100 kg) after which the depth of indentation is measured and the hardness number determined. For the improvised weapons, accuracy may vary depending on the surface curvature, finish and rigidity of the backing. Very small diameter spikes could not be measured due to the high curvature and size.

Push-through Tests

Quasi-static push-through tests were conducted with representative armor, Twaron Microflex® (550 DTEX) Special HS, to provide a rudimentary assessment of weapon system performance. The method involved placing a fabric sample in an Instron machine and clamping the sample around its periphery with slack removed,

Figure 7. A NIJ 0115.00 foam backing pack was placed in intimate contact with the sample bottom to provide some level of support and penetration measurement capability. A weapon was placed in the Instron head and clamped at the handle. The instantaneous force and displacement were measured until a maximum stroke of 25 mm was achieved. Actual penetration derived from the witness paper or backing penetration depth was not possible due to tearing and snap-through, respectively.

The number of layers of fabric was chosen to allow the majority of weapons selected to marginally perforate the fabric layers in order to obtain data on the force and work required to achieve perforation.

Selection of a robust armor system preventing perforation would not result in meaningful data. A total of 3 layers of Twaron Microflex® was selected for all tests.

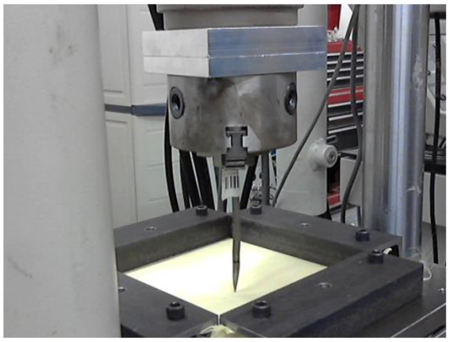
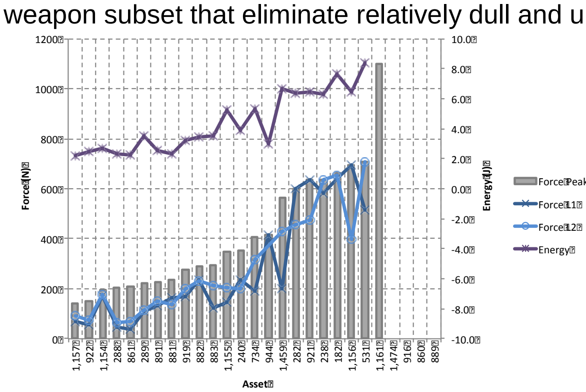


Figure 7: Push-through test.

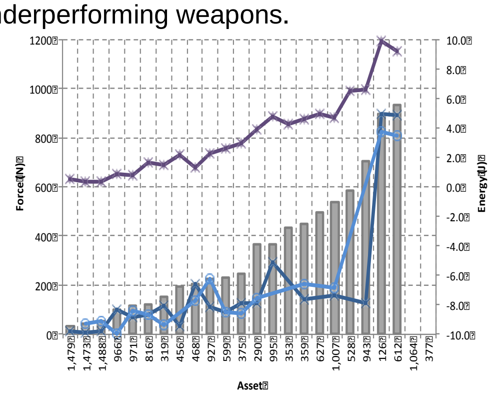
Results

The force data collected for the weapon subset is presented in Figure 8. The weapons are ranked by peak force measured during the controlled push-through tests. The corresponding forces required to perforate the first and second of the three layers of armor are also presented as Force L1 and Force L2, respectively. The maximum work or energy expended during the 25 mm stroke is also provided for each weapon.

It may be observed that the peak force corresponds well to the perforation forces of individual layers and that the energy also tracks with the peak force. These trends provide a basis for further creating a weapon subset that eliminate relatively dull and underperforming weapons.

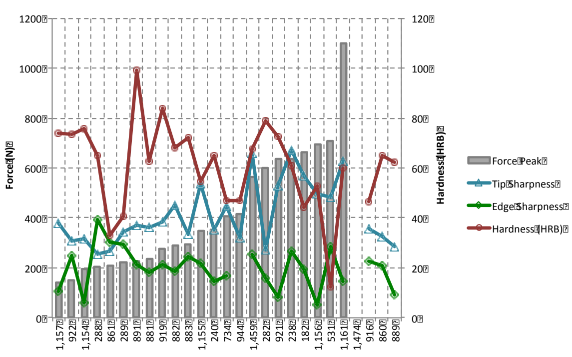


(a)

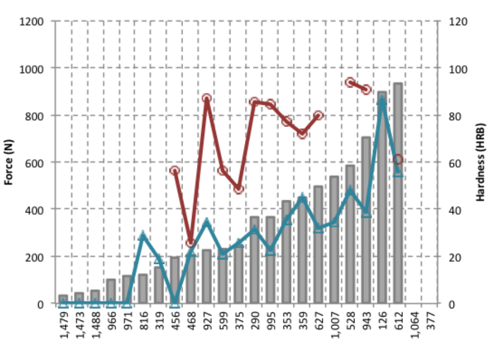


(b)

Figure 8: Quasi-static push-through test results; (a) blades; (b) spikes.



(a)



(b)

Figure 9: Test results for tip/edge sharpness and push-through; (a) blades; (b) spikes.

The tip and edge sharpness performance results of the weapon subset is presented in Figure 9 and are ordered by push-through force. The sharpness values reference the secondary axis and should be read as Newtons. No spike tip sharpness values were obtained for six weapons due to difficulty in performing the indentation test without significant bending of the weapon body.

The weapons with low peak forces tend to exhibit higher tip sharpness values (lower force) for both the blades and spikes. Edge sharpness for the blades did not correspond to peak force. Material hardness readings for the blades and spikes presented in the figures vary considerably and may be partly due to material composition, weapon geometry or support conditions. The average of three hardness readings were reported to reduce these variations.

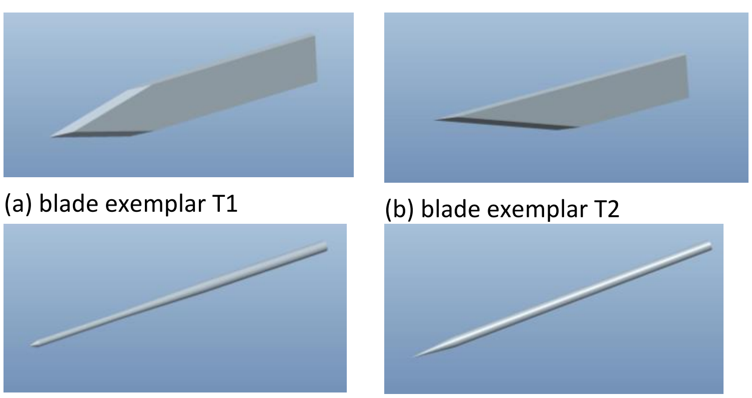
EXEMPLAR WEAPON DEVELOPMENT

Exemplar development was to be based on the geometric and physical attributes of the weapon subset identified from the quasi-static performance assessments. Upon analysis of the geometric and performance data from the weapon subset, it was decided to create a further subset of 9 bladed and 9 spiked weapons based on the push-through performance. No stakes were chosen due to the small test sample size and overlapping performance with the other weapon types. The selected blades and spikes together represent 1.3% of the weapon survey and those that display higher penetrative performance. An example of the bladed and spiked weapon subset is illustrated in Figure 10.

Figure 10: Sample bladed and spiked weapons.

Inspection of the bladed weapons revealed two distinctive blade styles; double-edged symmetrical and single edged with single grind. Similarly, two distinct spike styles were noted; a small diameter short-tapered tip and a larger diameter, long taper. From these, four exemplar specifications were created on averaged geometric and physical properties. The geometry of the exemplars was further influenced by the need to replicate the buckling modes and lateral flexural stiffness of the weapons in addition to maintaining, to the extent possible, compatibility with the NIJ 0115.00 test equipment and configuration.

The four exemplar types were denoted as: T1 - a blade with single sharp edge, single grind, asymmetrical taper with rectangular cross section; T2 – a blade with double edged, double grind, symmetrical taper with rectangular cross section; T3 – a spike of small diameter, short tapered tip, and; T4 – a spike of medium diameter rod and long tapered tip. These are illustrated in Figure 11. The materials for the blades were of mild steel with Rockwell Hardness “B” levels ranging from 55 to 80, *i.e.* much softer than the current NIJ 0115.00 threats.

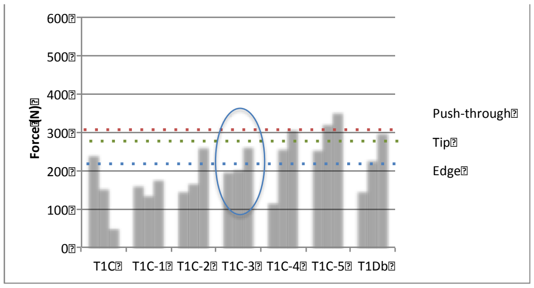


(a) blade exemplar T1
(b) blade exemplar T2
(c) spike exemplar T3
(d) spike exemplar T4

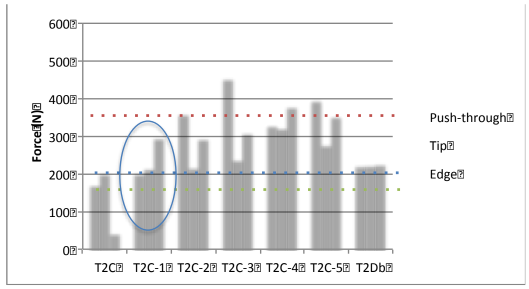
Figure 11: Depiction of the exemplar weapons.

The tip and edge sharpness specifications of the exemplars was based on trials with different levels of material ground from the tips and edges until a match was found with the averaged push-through performance of each weapon style. Comparison of the exemplar performance from single tests to the average survey weapon subset measurements is found in Figure 12 where the dashed lines represent the average weapon values and the dullness level denoted by the threat label suffix. The final exemplar selection is indicated by the ellipses.

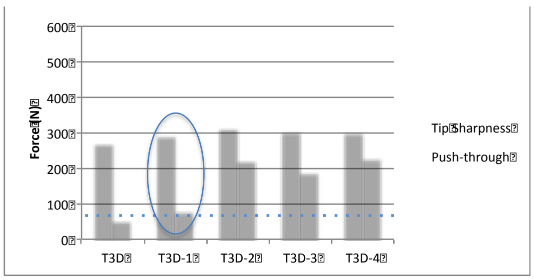
The bladed exemplars exhibited some push-through performance variability while the spikes tended to increase in push-through force as tip sharpness deceased. Disparity between the exemplar tip/edge sharpness measurements and the averaged weapon data was noted, however, the reasons for this are not fully understood but are thought to be attributed to differences in surface finish, edge geometry, and test variability.



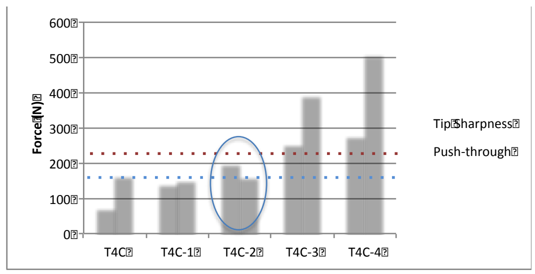
(a) T1 Exemplar



(b) T2 Exemplar



(c) T3 Exemplar



(d) T4 Exemplar

Figure 12: Exemplar quasi-static performance compared to weapon data (dashed lines).

Final performance assessment of the exemplars was carried out with dynamic drop tests with the objective of finding the number of layers required to meet the 7 mm penetration limit. The test methodology specified in NIJ 0115.00 (Level 3, E1) was used as a basis and augmented with a V_{50} type approach (e.g. MIL-662F, STANAG 2920, NIJ 0101.06), to estimate the number of armor layers required to meet the penetration limit with a 50% risk of failure. This so-called L_{50} level was established for the exemplars best matching the quasi-static performance of the weapon subsets and is presented in Table 4. Armor materials were chosen to best suit the bladed and spike type threats and resulted in less layers to defeat the proposed exemplars compared to published results for the P1/A and S1/G exemplars.

Table 4: L_{50} assessment results for all exemplars.

Threat	Armour	L50 Mean	Low	High	Std. Dev.
T1C-3	Twaron Aramid SRM 509/930, loose layup	12	10	13	1.3
T2C-1	Twaron Aramid SRM 509/930, loose layup	12	9	14	1.9
T3D-1	Twaron Aramid Fabric - Microflex 60" (550 DTEX) Special HS, loose layup	5	3	6	1.3
T4C-2	Twaron Aramid Fabric - Microflex 60" (550 DTEX) Special HS, loose layup	7	5	8	1.3

SUMMARY AND RECOMMENDATIONS

In summary, four exemplar weapons were developed to represent the treats found in correctional facilities and may be considered for future updates of relevant body armor performance standards such as NIJ 0115.00. The following findings and recommendations can be noted:

- a stab weapon typology and taxonomy were successfully developed to identify potentially aggressive threats based on descriptive information,
- quasi-static performance tests were developed to characterize tip, edge and system performance for initial down-selection of stab weapons, additional work is required to establish confidence levels and potential for quality control measures of the exemplars,
- two bladed and two spiked exemplar weapons were developed from the geometric and performance characteristics of a weapons obtained from correctional facilities in the US,
- the proposed exemplars require a lesser number of armor layers to meet the current penetration limits of NIJ 0115.00 in comparison to the P1/A and S1/G exemplars,
- greater use of the exemplars from the practitioners is required to fully understand their implications on armor design, relevancy and test variability.

Acknowledgements

The authors would like to acknowledge the NIJ for sponsoring the program and the guidance of the Special Technical Committee on stab and slash standards.

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FINAL REPORT

1. INTRODUCTION

This report is submitted in conjunction with Biokinetics '*Characterization of Weapons Used in Stab Attacks – Surrogate Development Final Report*' and details the work completed by Wayne State University (WSU) in reference to a National Institute of Justice (NIJ) Program entitled 'Characterization of Weapons used in Stab/Slash Attacks'. Whereby, WSU was contracted by the National Institute of Justice to provide scientific support and guidance to a new formed Special Technical Committee (STC), whose overall goal was to review and revise the current NIJ standard 0115.00 Stab Resistant of Personal Body Armor, to ensure that it accurately addresses the requirements of its current end user.

The National Institute of Justice develops performance standards to ensure the safety and effectiveness of the equipment used by law enforcement, corrections, and public safety practitioners in the United States (US). NIJ has produced more than 75 standards over the past 40 years.

1.1 NEW NIJ STANDARDS DEVELOPMENT PROCESS (Excerpts taken from: Stoe et al., Novel Approach to Body Armor Standards Development, Personnel Armour Systems Symposium, 2012.)

In an effort to ensure that its standards more accurately articulate the requirements of the user, NIJ created and implemented a standard development process that centers on and involves the practitioner from start to finish. The basis of this new process is a special technical committee (STC) made up of state, local, federal, and tribal practitioners and technical experts. Practitioners on the STC include law enforcement, corrections, and/or other criminal justice subject matter experts (SMEs) with experience relevant to a particular technology and who represent stakeholder organizations, such as the International Association of Chiefs of Police, the Fraternal Order of Police, the American Correctional Association, and the National Sheriff's Association. The practitioners were recruited from different regions of the US in order to obtain an array of experience and operational environments. In addition to expert practitioners, the STC also includes scientists, engineers, test laboratory personnel, and conformity assessment experts with relevant expertise. The final products of the STC are three related documents: the performance standard; the certification program requirements; and the selection and application guide.

1.2 STAB AND SLASH TECHNICAL COMMITTEE

Twenty nine (29) law enforcement practitioners and industry professionals were convened by the NIJ to review and revise the current NIJ stab/slash standard. Following a series of initial meetings, a number of areas within the standard were selected for improvement/revision. Data from the current effort was provided to the STC and feedback was garnered to elicit the best path forward.

As stated above, the new standard development process aimed to focus better on the environmental and ergonomic needs of the end user. Therefore to accurately articulate the requirements of all law enforcement users, part of the STC's work was to introduce a new section within the new stab/slash standard, which addresses the needs of a law enforcement officers based within a correctional facility setting.

Unlike civilian law enforcement officers, whose most likely threat to life (in reference to an assault) is from a firearm or commercially made bladed weapon, correctional facility-based officers are more likely to be exposed to the threat from an improvised or prison-fashioned weapon (due to the lack of available firearms or commercially made weapons within their environment).

1.3 DETERMINING THE THREAT

Three main threats were identified by the STC as the main areas of concern regarding assaults on officers in a correctional setting:

1.3.1 Stab threats. An improvised or prison-made weapon is generally constructed from wood, plastic, or a soft metal, hand fastened with a typical blade length of 4 to 6 inches. A stab attack is typically from behind the officer's back and is usually during response to an event within the facility. The attack usually occurs in close quarters with the officer being knocked down prior to being stabbed with short jabs. Practitioners noted that an officer is more likely to be stabbed in the torso than in the extremities. Due to metal detectors and other detection technologies in place within correctional facilities, it is very difficult to introduce weapons, therefore commercially made knives are not considered to be the primary threat.

1.3.2 Slash threats. A second threat is an edged weapon used to slash at an officer. Examples of slash weapons include sharpened can lids; sharpened metal taken from such items as bed frames, overhead lighting fixtures, or lockers; and razor blades on toothbrushes. Practitioners noted that an officer is more likely to be slashed in the extremities than in the torso.

1.3.3 Blunt trauma threats. Blunt trauma threats, including hand-delivered weapons or kicking, are the third type of threat faced by corrections officers. Examples of hand-delivered weapons include bats, mop handles, and metal or wooden rods.

It was decided, following discussion with the NIJ and lead STC members, that with the current time and budgetary restrictions placed on the project, it would not be possible to investigate all three threats listed above fully, therefore the research scope focused on stabbing threats.

1.4 LITERATURE REVIEW

Two primary modes of knife attack have been identified in the literature, thrust and slash attacks [Chadwick, Nicol et al. 1999; Horsfall 2000; Watson, Horsfall et al. 2000; Carr, Kemp et al. 2010]. Thrust attacks may involve a plunge and drag phase while slash attacks involve a more lateral sweep across the body. The effect of the attack mode on body armor construction can be large with thrust attacks requiring thick, heavy armor to defeat penetrating threats [Chadwick, Nicol et al. 1999; Bleetman, Watson et al. 2004; Croft and Longhurst 2007]. In contrast, slash attacks can be resisted with lighter, more flexible armor.

Table 5: Summary of stab attack inputs and response against armor.

Attack speed	8.4 m/s
Momentum transfer	68 kg m/s
Energy transfer	69 J
Peak measured axial force	1885 N

In the published studies, three modes of bladed weapon use were established in consultation with police; a short forward thrust, overhand stab and horizontal sweep [Chadwick, Nicol et al. 1999]. Each style produced unique loading characteristics measured with an instrumented handle. Volunteers from the police force conducted tests on a Kevlar armor mounted on foam and clay targets. The 95th percentile values of stab attack inputs are presented in Table 5.

The loads were commented to be high as a result of the strength and skills of the volunteers. Suggestion was made to provide multiple levels of performance to match different threat situations. High lateral and torsional loads were also noted and primarily associated with the horizontal sweep. Blade strength and rigidity and handle design were viewed as an important aspect of the weapon in order to withstand these loads.

In a study of simulated slash attacks, differences in delivery method and initial strike velocity were noted. Experiments with volunteers resulted in slash impact speeds in the range of 6-10 m/s but achieved peak forces 25% lower than found for stabbings [Chadwick, Nicol et al. 1999; Watson, Horsfall et al. 2000]. Impact speeds for stab were found to be similar for thrust and overhand approaches, 6.6-12 m/s [Miller 1998]. In another study, Bleetman, [Bleetman, Watson et al. 2004], reported on simulated slash attacks based on the test methods and data of Watson, [Watson, Horsfall et al. 2000]. Horizontal and diagonal slash patterns were studied with Kevlar and foam targets with a witness paper facing. Student volunteers were used and the 95th percentile values for all attack modes are presented in Table 6. The reaction forces are considerably less than for stab, supporting the notion that less robust armor is required to resist slash attacks.

Table 6: Summary of slash attack inputs and response against armor.

Attack speed	10.6 m/s
Peak measured force	175 N

Physical attributes responsible for failure of the target are proposed to involve the following.

- The tip of the weapon is responsible for initiating perforation of the target possibly leading to reduced effort for subsequent penetration and creation of an opening for wedging action of the tool. The opening may involve crack propagation for some materials.
- The edge of the weapon provides a cutting action, which can lead to material separation (*e.g.* parting, wedging, material removal and cracking) depending on the angle of attack, bladed design (*e.g.* serrations), target materials and push/slice force ratio.
- The surface finish of the tip, edge and blade due to the high normal forces involved with the weapon as it penetrates into the target material.

There are several key factors to consider when assessing the injury potential of a given weapon; however two key factors that have been identified include tip and edge sharpness (Watson, Horsfall et al. 2002). The ability of a weapon to cut is in essence its sharpness. This variable can be determined using several proposed techniques (McGorry, Dowd et al. 2005; McGorry, Dowd et al. 2005; Marsot, Claudon et al. 2007; Gilchrist, Keenan et al. 2008). However, to determine tip sharpness, the current NIJ 0115.0 Stab Resistance of Personal Body Armor uses a modified Rockwell Hardness Testing machine. Materials can be tested to determine their Rockwell hardness. This is done by applying a minor load directly prior to a major one. The depth of penetration into a standard material is then noted; the harder the material the higher the number. The 0115.0 standard uses minor (3 kg) and major (5 kg) loads which produce an overall load of 8 kg. The standard indenter is replaced by the exemplar being tested and the sample block being indented is made of at least 5 mm thick 99.997% aluminum. Conversion of the indentation depths to hardness on the Rockwell C scale is provided within the standard. Currently the standard requires all exemplars used in testing shall be between -50 and -150 on the Rockwell C scale.

Although there has been substantial work in the area of stab/slash implements in the United Kingdom (Connor, Bleetman et al. 1998; Bleetman, Watson et al. 2003; Bleetman, Watson et al. 2004), there was limited data that has been collected in the United States. The current NIJ 0115.0 Stab Resistant Standard uses exemplars that were based on data collected outside of the United States. Given the varying threat exposures between countries, it was important to adequately assess the types of threats being encountered in the United States.

2. METHODS

The weapon study was divided into three phases, each with their own individual goals. WSU worked in partnership with Biokinetics, who was responsible for the design of exemplars that were proposed for inclusion of any updated standards.

2.1 Phase 1

2.1.1 Part A – Survey of weapons

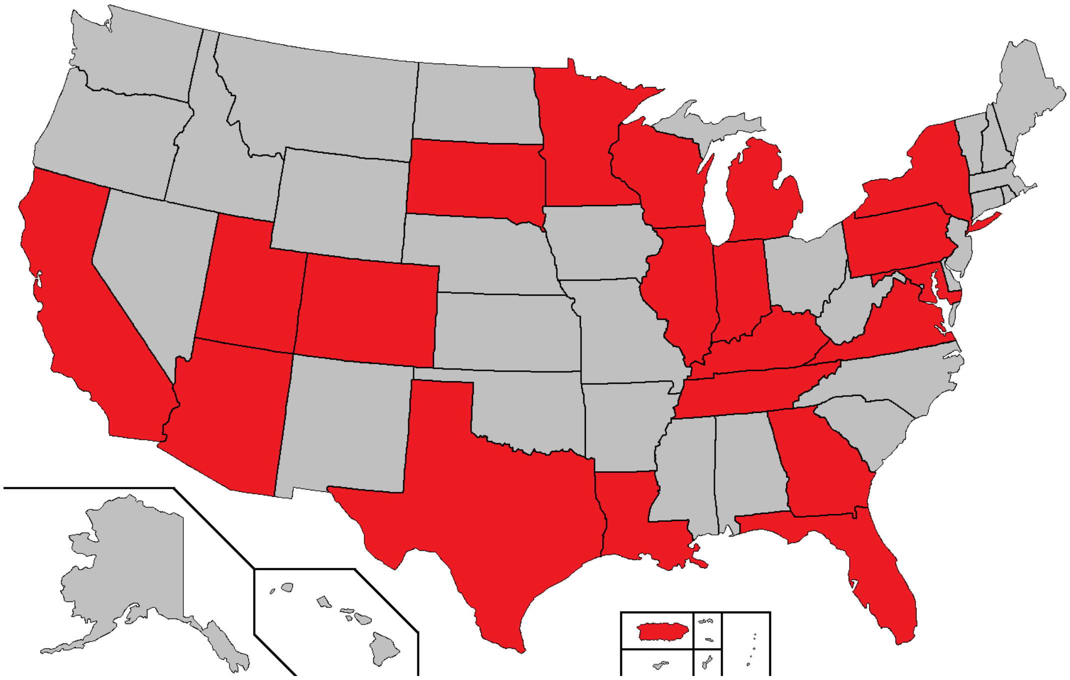
The survey of existing weapons was completed in two stages. The first stage involved procuring weapons through contacts of the Special Technical Committee (STC) members. This resulted in collecting 927 improvised weapons from 11 different states. For the second stage, WSU liaised with Bruce Blair from the National Law Enforcement and Corrections Technology Center and Joe Russo from the Corrections Technology Center of Excellence to target geographical areas that were not currently represented in our sample. A total of 1353 weapons were procured through the two collection stages from 20 different states (see Table 7 and Figure 13). (Refer to Appendix A for further information on the various prison systems within the United States of America)

Table 7: Correctional facilities surveyed for study.

Name	City/Town	State	Type	Security Level	Established	Avg Population
FCI Greenville	Greenville	IL	Federal	Min to Med	Unknown	1200
USP Big Sandy	Inez	KY	Federal	Min to Max	2003	1432
USP Tucson	Tucson	AZ	Federal	Med to Max	2007	1580
FCI Big Spring	Big Spring	TX	Federal	Low	1979	1800
USP Lee	Lee County	VA	Federal	Maximum	2002	1472
FCI Victorville	Victorville	CA	Federal	Medium	2004	1300
FCI Pekins	Pekins	IL	Federal	Medium	1994	Unknown
USP Atwater	Merced County	CA	Federal	Maximum	2001	1350
FCI Florence	Fremont County	CO	Federal	Medium	Unknown	1100
FCI Ray Brook	North Elba	NY	Federal	Medium	1980	1190
MDC Guaynabo	Guaynabo	Puerto Rico	Federal	Multi-Level	Unknown	Unknown
FCI Mckean	Lafayette Township	PA	Federal	Medium	1989	1500
FCI Oxford	Adams County	WI	Federal	Medium	Unknown	1000
FCI Otisville	Town of Mount Hope	NY	Federal	Medium	1977	1775
USP Atlanta	Atlanta	GA	Federal	Medium	1902	1940
USP Pollock	Grant Parish	LA	Federal	High	Unknown	1350
USP Terre Haute	Vigo County	IN	Federal	High	1940	1480
Branchville Correctional Facility	Branchville	IN	State	Min to Med	1982	1436
Minnesota Correctional Facility-Oak Park Heights	Stillwater	MN	State	Maximum	1982	434
Utah State Prison – Draper	Draper	UT	State	Multi-Level	1951	4500
Central Utah Correctional Facility	Gunnison	UT	State	Multi-Level	1990	1600
Jackson Correctional Institution	Malone	FL	State	Maximum	1991	1350

"California Institution for Men	Chino	CA	State	Min to Max	1941	2976
Maryland Correctional Institution - Jessup	Jessup	MD	State	Med to Max	1991	1700
MD Correctional Institution – Hagerstown	Hagerstown	MD	State	Medium	1942	2100
Tennessee Department of Corrections	N/A	N/A	State	N/A	N/A	N/A
Barage Correctional Facility (AMF)	Barage	MI	State	Multi-Level	1993	Unknown
Earnest C Brooks Correctional Facility	Muskegon Heights	MI	State	Multi-Level	1989	Unknown
Kinross Correctional Facility	Kincheloe	MI	State	Min to Medium	1978	Unknown
Michigan Reformatory	Ionia	MI	State	Multi-Level	Reopened 2007	Unknown
South Dakota State Penitentiary	Sioux Falls	SD	State	Maximum	1881	Unknown
Pugsley Correctional Facility	Fife Laketownship	MI	State	Minimum	1956	1342
Lakeland correctional Facility	Coldwater	MI	State	Minimum to Medium	1985	Unknown

Figure 13: Map of states where improvised weapons were collected (states in red provided weapons).



2.1.2 Part B - Weapon Typology

Upon receipt at WSU, the improvised weapons were photographed, bar coded for inventory purposes, and then grouped into one of four style categories to represent the general construction and mode of use. The weapon classification definitions are provided in Table 8**Error! Reference source not found.**. This initial categorization of blades represented one level of segregation implemented at the beginning of the current effort. The taxonomy scheme attempted to treat all weapon attributes and characteristics in the general case so as not to bias the analysis. These weapon style definitions remained during the taxonomy effort.

Table 8: Description of weapon style.

Weapon Style	Description
Blade	Flat blade with rectangular cross section generally having a tip, edge and handle. To be used in a thrust mode and possible drag/slash follow-through.
Ice Pick	A typically round shaft construction having a tip, slender shaft and handle. To be used in a thrust mode.
Stake	Similar to the blade but with an irregular cross section.
Slash	A small flat blade generally without a tip but having a supporting handle. The blade may be oriented perpendicular to the handle. To be primarily used in a slashing or sweeping mode.

A list of parameters was developed to describe the physical characteristics that were related to the lethality of the improvised weapon. Table 9 below lists the broad parameters recorded for each weapon.

Table 9: Parameters collected for each improvised weapon procured.

Parameter	Context
Weapon Style	Knife, Spike, etc.
Mode of Use	Overhand, Underhand, Thrust, Slash, Thrown
Blade Construction Description	Robustness and Penetrability
Handle Description	Weapons Delivery Effectiveness
Surface Finish of Blade (Roughness, Striations, Orientations)	Friction Interaction with Body Armor
Blade Dimensions (length, width, thickness)	Penetrability
Slimness or Aspect Ratio of Tip	Frictional resistance
Tip Sharpness	Penetrability
Edge Sharpness	Cutting of Armor
Material Compositions	Penetrability

A structured approach to data entry was required to obtain consistency of the entries and to ensure an appropriate structure for computer-aided data analysis. The data entry requirements in Table 10 were needed for each weapon in the survey and therefore an Excel® worksheet was developed. To aid with data entry and analysis, the worksheet was formatted with standard database conventions utilizing records and fields (Appendix B). The worksheet provides the data requirements for the classifications and includes field entries, processed data, nomenclature, definitions, revision record, analysis tables and plots. Extensive data error checking and confirmations were conducted to help ensure integrity of the database. The majority of the data analysis, down selection and processing was conducted within the database/worksheet making it useful for the addition of weapons or for revising the analysis rules and processes. A complete listing of the database entries can be found in Appendix C.

Table 10: Initial descriptive weapon taxonomy.

Phase		Attribute	Level I - Typology	Level II - Effective-ness	Level III - Exemplar Development
Asset Type		**Agency Type**	**X**	**X**	**X**
		Overall Length (mm)	**X**	**X**	**X**
		Overall Weight (g)	**X**	**X**	**X**
		Style	**X**	**X**	**X**
		Original Item Description	**X**		
Tip	**Description**	**Material**	**X**	**X**	**X**
		Shape Description	**X**	**X**	**X**
	Geometry	**Radius (mm)**		**X**	**X**
		Cone (deg)		**X**	**X**
		Width, Dia. (mm)		**X**	**X**
		Length (mm)		**X**	**X**
		Surface Finish		**X**	**X**
		Hardness		**X**	**X**
Edge	**Description**	**Shape**	**X**	**X**	**X**
		Condition	**X**	**X**	**X**
		No. Edges	**X**	**X**	**X**

Phase		Attribute	Level I - Typology	Level II - Effective-ness	Level III - Exemplar Development
	Geometry	**Edge No.**		**X**	**X**
		Radius (mm)		**X**	**X**
		Cone (deg)		**X**	**X**
		Cannel (mm)		**X**	**X**
		Grind sides		**X**	**X**
		Distance from Tip - Start		**X**	**X**
		Distance from Tip - Stop		**X**	**X**
		Length (mm)		**X**	**X**
Blade/Body	**Description**	**Material**	**X**	**X**	**X**
		Shape - planar	**X**	**X**	**X**
		Spine	**X**	**X**	**X**
		Serrations (describe)	**X**	**X**	**X**
		Width (mm)	**X**	**X**	**X**
		Length (mm)	**X**	**X**	**X**
		Thickness Max. (mm)	**X**	**X**	**X**
	Geometry and Material Characteristics	**Surface Finish**		**X**	**X**
		Hardness		**X**	**X**
		Diameter (mm)		**X**	**X**
		X-sec (no. corners + edges)		**X**	**X**
Handle	**Description**	**Cover**	**X**	**X**	
		Length (mm)	**X**	**X**	
		Tang	**X**	**X**	
		Guard	**X**	**X**	
Performance Evaluation	**Requirements**	**Stab**		**X**	**X**
		Other		**X**	**X**
		Blunt Trauma		**X**	**X**

Implementation of the database was carried out in a stepped approach to cope with the large amount of weapons from the survey. Three levels of activity were carried out as described in Table 11 and incorporated the taxonomy processes of characterization, ranking and assimilation.

Table 11: Description of various stages of weapon database population.

Level I Characterization	An initial effort to characterize the weapons based on coarse geometric measurements and qualitative descriptors.
Level II Effectiveness	A detailed characterization of a weapon subset based on a down selection process of the Level I information. The characterization effort is to include performance measures of weapon attributes and system.
Level III Exemplar Development	Further characterization of a weapon subset from the Level II information including processed information for the development of the exemplars.

The first level catalogues the attributes of the weapon responsible for its performance. The data are used for subsequent rankings and analysis for down selection of the weapons. The second level catalogues the effectiveness of the down selected weapons in defeating body armor. Effectiveness is assessed either by the geometric and material characteristics of the weapon, i.e. tip/edge sharpness, and by actual experimentation with representative armors allowing the weapon performance to be evaluated. The test methods developed at WSU were used as a basis for collecting performance data and comprises a controlled quasi-static push-through test with the force required to initiate perforation and subsequent push-through being documented for a sample armor. Representative armor systems are used to address differences in correctional and commercial weapon aggressiveness. The performance data was used to further down select the weapons for subsequent classification and development of the exemplars. The third level quantifies the geometric and physical attributes of the down-selected weapons for the purpose of developing exemplars. Detailed information on the geometric, material and surface characteristics is required and heavy reliance is placed on the down-selected weapon group from the previous classification effort.

2.2 Phase 2 – Weapon Typology/Improvised Weapon surrogate development

Biokinetics (subcontractor) developed a typology for the improvised weapon exemplar, using the knowledge gained in phase 1 by WSU and from an approach that involved the key components of how delivery occurs and the armor interaction with the weapon. The goal was to have specific classifications based on threat to life.

2.2.1 Final Weapon Typology Based on Measurement of Weapon Values and Down Selection

A Multiple Criteria Decision Making (MCDM) process was used to consolidate and rank the weapon information. In principle, a weighted objective function is defined based on fundamental weapon attributes that contribute to its performance. It has the form:

$$Objective = \sum_{i=1}^{n} W_i(C_i)$$

Where:
C = the objective criteria,
W = the weighting factor,
N = the number of criteria.

Each criteria, whether it was a descriptor of an attribute or assessment of performance, was prioritized in accordance to contribution to performance. The sum of all the prioritized criteria then reflects the overall performance of the weapon. When completed for each weapon, the values can be ranked and grouped to identify those with the propensity to perform more effectively.

Establishing the priorities or weighting factors for the criteria based solely on descriptive information is problematic as qualitative and quantitative information is used. To address this, a subset of the MCDM process called the Analytic Hierarchy Process (AHP) was used [Saaty and Vargas 2006]. The AHP allows for consistent ranking of seemingly disparate criteria. It involves creating relative linear or non-linear rankings of paired criteria comparisons while providing an assessment of consistency between the rankings. Further, it can be applied to multilevel hierarchic structures where multiple objective functions are used, typically from low level to more global assessments.

AHP criteria in this study took into account weighted contributions from the tip, edge and blade of the weapon. Similarly, the effectiveness of the tip, for example, was based on the weighted contributions of the tip perforation performance, which in turn was based on the weighted contributions of material, cone angle, diameter/thickness and length. This hierarchical process was applied to the edge and blade. The criteria are defined below and use information directly from the topology database and data from performance estimates based on a combination of database entries. The weighting factors are denoted by the lower case letters, which were determined for each application level of the AHP. More details of the procedures are provided in the Biokinetics Final Report, including Figure 10, which outlines the process for obtaining Weapon Values.

Weapon Value WV = a(TV) + b(BV) + c(EV)	Eqn. (7) from Biokinetics Report

where:
WV = the system level assessment of the weapon performance,
TV = Tip Value, performance assessment of the tip,
BV = Blade Value, performance assessment of the blade,
EV = Edge Value, performance assessment of the edge,
a, b, a = weighting factors determined from the AHP.

It is recognized that this is an approximation of the weapons true performance but until experimentation can be conducted with a small set of down selected weapons this is considered an acceptable means to rank the information.

2.2.2 Weapon Characterization Requirements

After completion of the initial descriptive typology and down selection, a higher degree of detail was required on weapon performance and geometry for development of the exemplars. An approach was used in which an appropriate performance test of the tip, edge and blade was administered to the down selected weapons. This method is consistent with the NIJ and HOSDB standards for assessing tip sharpness, for example. The performance tests were expanded to include push-through performance, tip sharpness, edge sharpness, blade hardness and flexural stiffness. Details of the tests are provided in the following sections.

The sample size for the weapon performance tests is provided in **Table 12**. The numbers differ from the down selection sample size due to weapon breakage or deterioration when executing the tests or due to data artefacts or non-representative weapon construction.

Table 12: Weapon down selection sample sizes and performance tests.

Style	Performance	Tip	Edge Sharpness	Blade Hardness	Flexural Stiffness
Bladed	30	26	25	26	9
Ice-pick	25	21	0	13	2
Stake	11	7	1	6	0
TOTAL	**66**	**54**	**26**	**45**	**11**

2.2.3 Performance Testing

Following the completion of the initial weapon typology, the data was processed by Biokinetics and a smaller subset of weapons was appropriated for further analysis. The weapons chosen for down selection were determined to be the most likely high preforming weapons, based on geometric characteristics. Although the initial geometric data collected gives an indication on how the weapons are likely to perform, the crudeness of the construction of the weapons and therefore lack of truly precise measurements, means alternative performance testing is required in addition to the geometric data.

Since existing research suggests that some of the main characteristics which affect the lethality of a weapon are the tip strength, flexural stiffness of the weapons shaft, and blade sharpness, these three characteristics were tested, as well as testing weapon performance against already existing armor system. The following section describes the performance testing that WSU carried, based on input from Biokinetics.

Tip Test

The most current methods for tip and edge sharpness evaluations have been proposed in the HOSDB Spike and Knife Resistance standard and the HOSDB Slash Resistance standard [Malbon and Croft 2006; Croft and Longhurst 2007]. The NIJ 0115.00 stab resistance standard adopted similar tip sharpness test methods. The methods relate the penetrating force to indentation as a means to quantify the degree of sharpness and can therefore be used as a relative ranking method for the weapons surveyed. Absolute ranking will only be possible through dynamic testing of actual or simulated weapons with armor systems.

In the current study, tip sharpness was assessed with a quasi-static test setup similar to the methodology used by the NIJ 0115 and HOSDB standards. The operating principle is based on replacing the indenter of a hardness machine with the tip of the weapon and measuring the resisting force during indentation. Changes were made from the standard methodology in that a constant 3 mm indentation depth was used and the corresponding force measured. This methodology provides constant interaction with the tip and was felt to better represent the interactions with armor systems. Further, the indentation block (Figure 14) was changed from pure aluminum to pure lead in order to not damage the softer metals used in the improvised weapons gathered in the study.

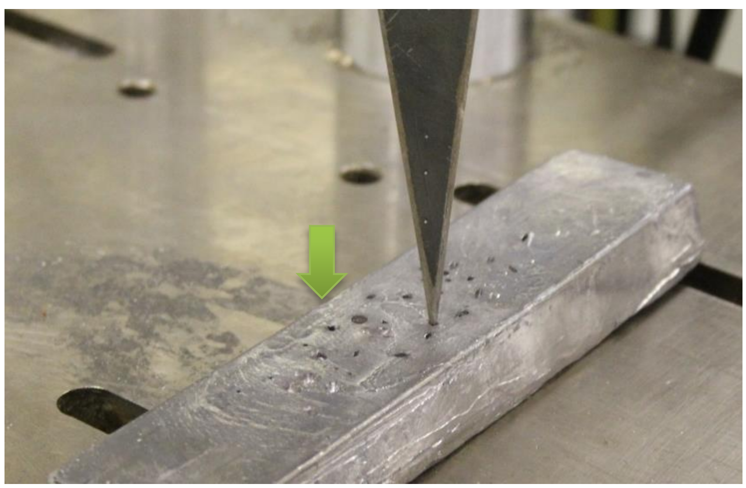


Figure 14: Tip sharpness indenter test setup.

All testing was performed by WSU and the results were entered into the weapon database. A typical response curve is provided in Figure 15. A lower force would correspond to greater tip sharpness.

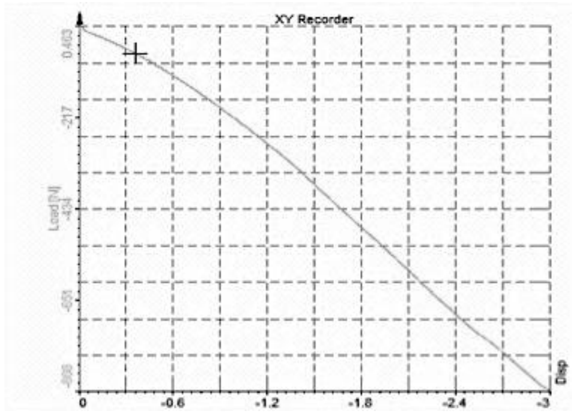


Figure 15: Typical tip resistance force response.

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Edge Sharpness

The edge sharpness test methodology was based on the principles proposed by Watson which measure the force required to press the edge of a weapon into a silicone rubber substrate [Watson, Horsfall et al. 2002]..For the current study, measuring the force required to press the edge of the blade into a silicon strip of constant width at a given depth assessed the initial edge sharpness. The tip was aligned with the front edge of the silicon rubber and the edge was parallel to the surface. The portion of blade edge interacting with the silicon was controlled by the width of the rubber strip. The rubber strip is wrapped around a rod to provide some surface tension as the edge cuts through the surface, thereby reducing interaction with the sides of the blade and reducing frictional effects, as intended by the CATRA test methods (Figure 16). The above method provides an approximation of the edge sharpness although dynamic effects are ignored, as are potentially different edge interactions with various armor systems (i.e. fabric, chainmail, metal/ceramic plates).

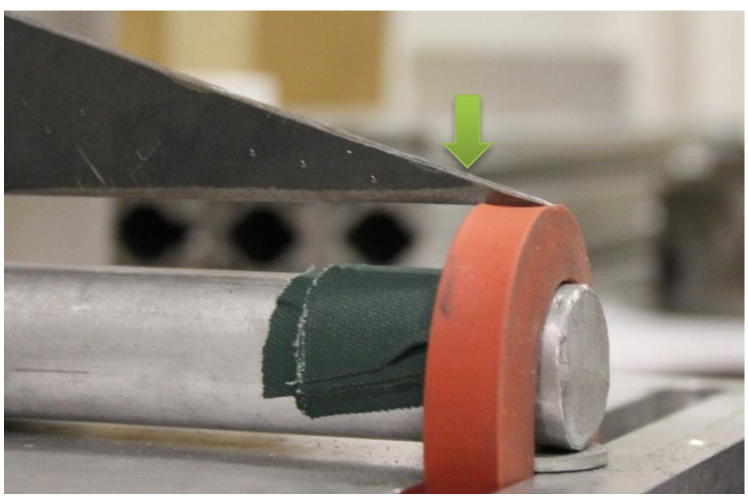
Figure 16: Edge sharpness test setup.

Weapon Hardness

Knowledge of the weapon's blade material strength is important to provide an assessment of the tip, edge and blade integrity. Weapon material strength can be inferred from its hardness, as this is commonly used as an indicator of the strength of material, or more specifically, the yield strength. A standard Rockwell indenter test method was employed to determine the hardness of each weapon (Figure 17). The Rockwell "B" scale was used as it is well suited for use with soft metals such as steel, aluminum and brass. Due to the small size of the indenter it provides local hardness measurements and is less susceptible to surface flatness deviations. For comparative purposes, a Rockwell "B" scale value of 120 is equivalent to a Rockwell "C" scale value of 55, i.e. similar to that of the current NIJ 0115.00 "P1/A" and "S1/G" stab threats. The hardness test method employs a Rockwell tester to apply a standard preload to the indenter followed by a major load (100 kg) after which the depth of indentation is measured and the hardness number determined. It uses a 1.59 mm steel sphere as the indenter.

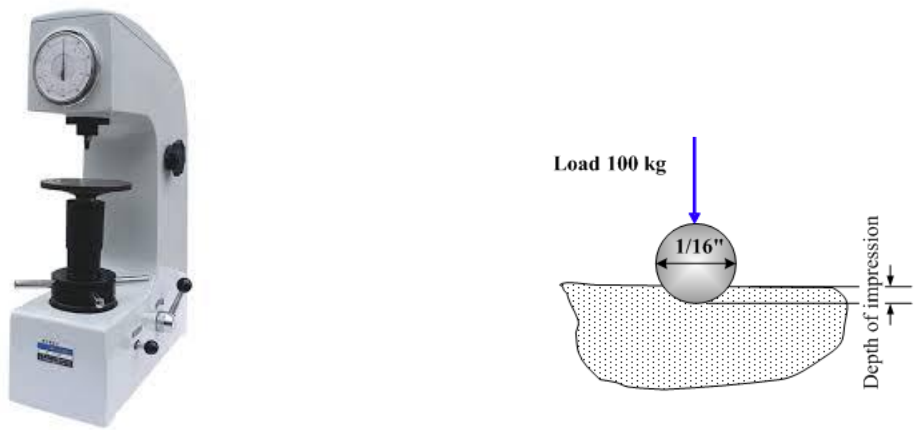

Figure 17: A typical Rockwell Hardness tester and Rockwell "B" spherical ball indenter.

The accuracy of the hardness measurements depends on the surface condition of the test sample. For best results, surface curvatures should be large so that the irregularities are small relative to the size of the indenter.

Push-through Tests

A method was sought to assess the overall weapon system performance incorporating the tip, edge, and blade but in a simple manner compared to the NIJ0115.00 test protocol due to the non-standard construction methods and relative frailty of the weapons. An initial trial at WSU, incorporating layers of clamped fabric armor and measuring the force required to push the weapon through the layers, was deemed sensitive enough to segregate the higher performing weapons. This method was later refined and used to assess the performance of the down-selected weapons as described below.

The use of simple quasi-static test methods to assess weapon performance is not new and forms the basis for many sharpness test methods proposed by CATRA and others. In fact, the tip and edge sharpness tests reported on earlier are also quasi-static in nature and provide quantitative measure of performance. The peak force obtained during the push-through tests was purported to correlate well with dynamic drop tests of the NIJ 0115.00. (Personnel communication - body armor industry representatives) The American Society for Testing and Materials (ASTM) also has several methods for assessing fabric cutting and puncturing, utilizing quasi-static loads (ASTM F1790, ASTM F1342) as referenced in NIJ 99-114 for glove performance testing.

The push-through test method consisted of clamping an armor system in place around its periphery to prevent slippage, Figure 18 and Figure 19. A method was developed to remove slack in the system without pre-tensioning the fabric. The improvised weapons were mounted within an Instron machine and the force-displacement relationship was measured. These measurements were used in conjunction with the dynamic drop tests to determine ranking.

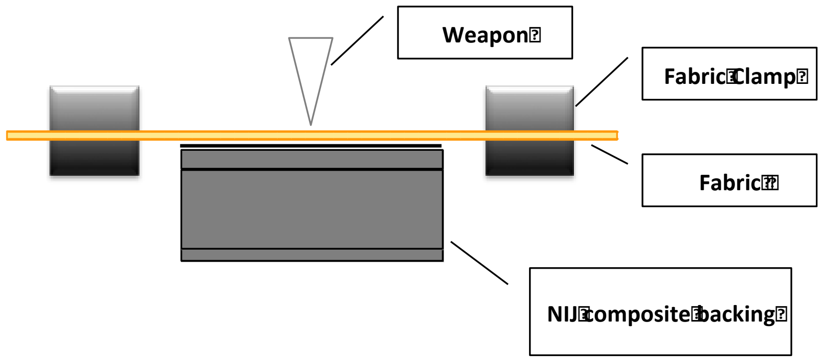

Figure 18: Push-through test components and setup

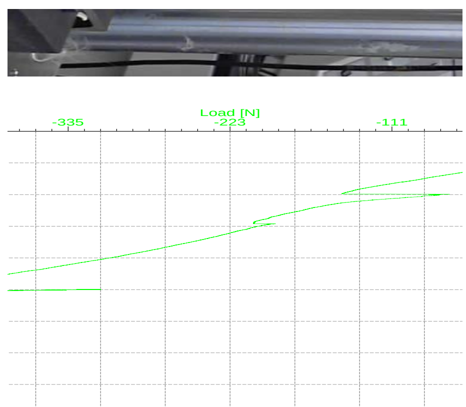

Figure 19: Push-through test setup (courtesy of WSU).

The test metrics measured included: the instantaneous force and displacement of the driving head of the Instron machine, the instantaneous work performed by the weapon, the number of armor fabric layers perforated, the residual penetration and notation of the fabric failure mode.

The residual penetration was measured by the number of Neoprene® rubber layers in the NIJ backing pack damaged by the weapon measured in 7 mm intervals. Proposed methods to measure instantaneous penetration were not achieved due to the complexity of the setup required. Attempts to measure the actual level of penetration with the NIJ backing witness paper was not successful due to premature rupturing of the paper during the stroking phase.

The armor material selected for the tests was based on discussions within the STC. It was indicated that the most common armor system was DuPont's Kevlar® Correctional™, Twaron's Microflex® or SMR 509 aramids, depending on the threats to be defeated. For the current investigation of the correctional weapons, Twaron Microflex® 60" (550 DTEX) Special HS, was chosen. Attempts were made to look at novel armor systems including metal plates, metal fibers woven into aramids and laminated weaves but cooperation from the suppliers was lacking despite high initial interest in the program's objectives.

The number of layers of fabric was chosen by WSU to allow the majority of weapons to marginally perforate the fabric layers as a minimum in order to obtain data on the force and work required to achieve perforation. Selection of a robust armor system preventing perforation would not result in meaningful data regarding the penetrability of the weapon. A total of 3 layers of Twaron Microflex® was selected for use in the test series.

The test protocol involved placement of the weapon against the clamped armor fabric, placement of the backing material and execution of the test until the test was aborted. Four criteria were used to aborting a test:

- Weapon failure, fabric slippage, weapon clamp slippage
- Perforation in excess of 7 mm (current fail criteria in NIJ 0115.00)
- Peak perforation force exceeding human capacity [Chadwick, Nicol et al. 1999], 1885 N
- The work performed exceeds human energy capacity [Chadwick, Nicol et al. 1999], 62 J

A draft protocol, measurement method and reporting requirements document was prepared to guide the test series. All results were entered into the weapon typology database for subsequent analysis. The weapons data entry table developed to meet these goals is attached in Appendix B.

2.3 Phase 3 – Exemplar Weapon Comparison

The final phase of the program was to compare the relative performance of the new improvised weapon exemplars to the P1, S1, and Spike threats found in the NIJ 0115.0 standard. Statistical analysis was completed to evaluate the newly developed exemplar(s) and their relative performance in relation to threat to life. Further details of the methodology are provided in the Biokinetics Final Report (Appendix D).

Results

3.1 Weapons Survey

A total of 1353 weapons were procured through the two collection stages from 20 different states (see Table 3). The weapons were subsequently photographed, measured and entered into a weapons database. Appendix C contains the detailed data entry for each of the procured weapons.

3.2 Weapon Typology

The weapons were initially classified into four styles as provided in Table 8 with the distribution of styles presented in Figure 20.

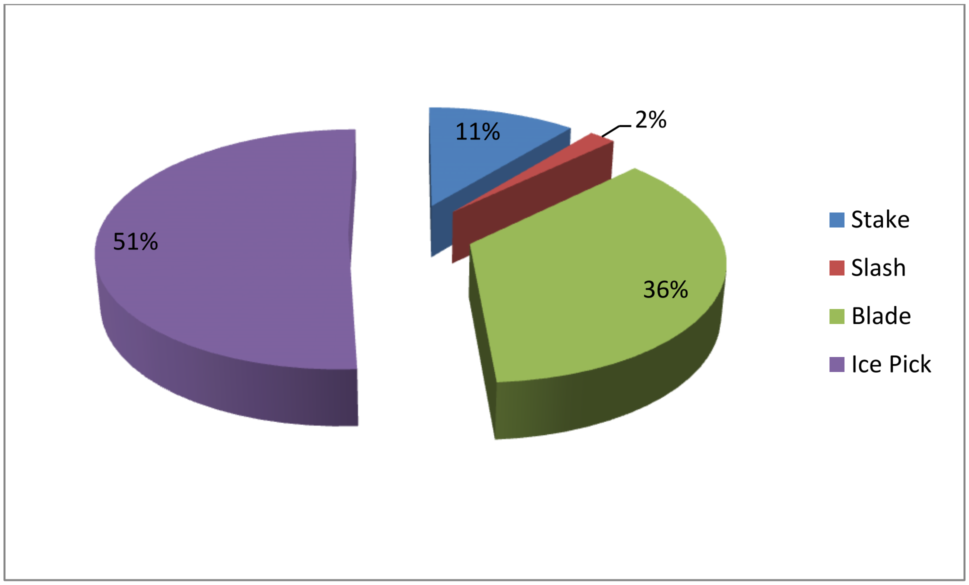

Figure 20: Distribution of Weapon Styles

3.3 Performance Testing

3.3.1 Tip Test

The tip test results for the down-selected samples are presented within the weapons database (Appendix C) and provided graphically in Figures 21 and 22 for bladed and spiked weapons, respectively. No stake data is presented as these were removed from further analysis due to the limited sample size and equal or lesser performance compared to the other weapons.

3.3.2 Edge Sharpness

The edge sharpness test results for the down-selected samples are presented within the weapons database (Appendix C) and provided graphically in Figures 21 and 22 for bladed and spiked weapons, respectively. Again, no stake data is presented for the same reasons stated in the tip sharpness tests. The data was reviewed and artifacts noted.

3.3.3 Weapon Hardness

The weapons hardness test results for the down-selected samples are presented within the weapons database (Appendix C) and provided graphically in Figures 21 and 22 for bladed and spiked weapons, respectively.

3.3.4 Push-through Tests

The force data collected for the down-selected blade and spike weapons were provided by WSU and are presented in Figure 21 and **Figure 22**, respectively. The weapons are ranked by peak force measured during the controlled push-through tests. The corresponding forces required to perforate the first and second of the three layers of armor are also presented as Force L1 and Force L2, respectively. The maximum work/energy expended on conducting the tests is also provided for each weapon.

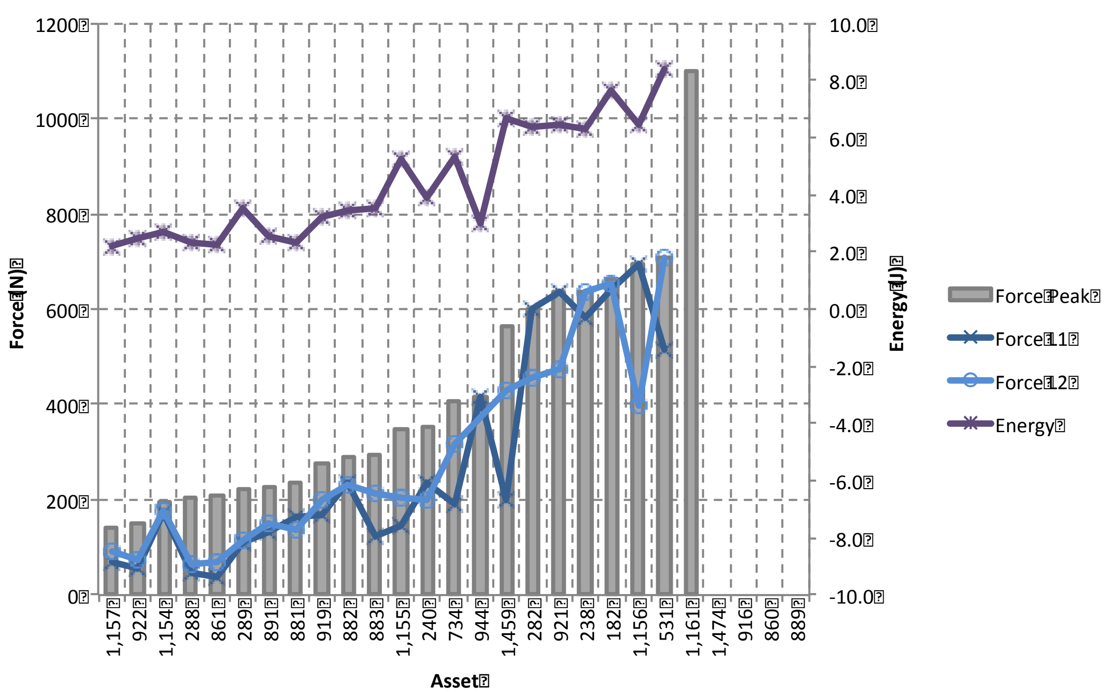

Figure 21: Push-through bladed weapon force test results.

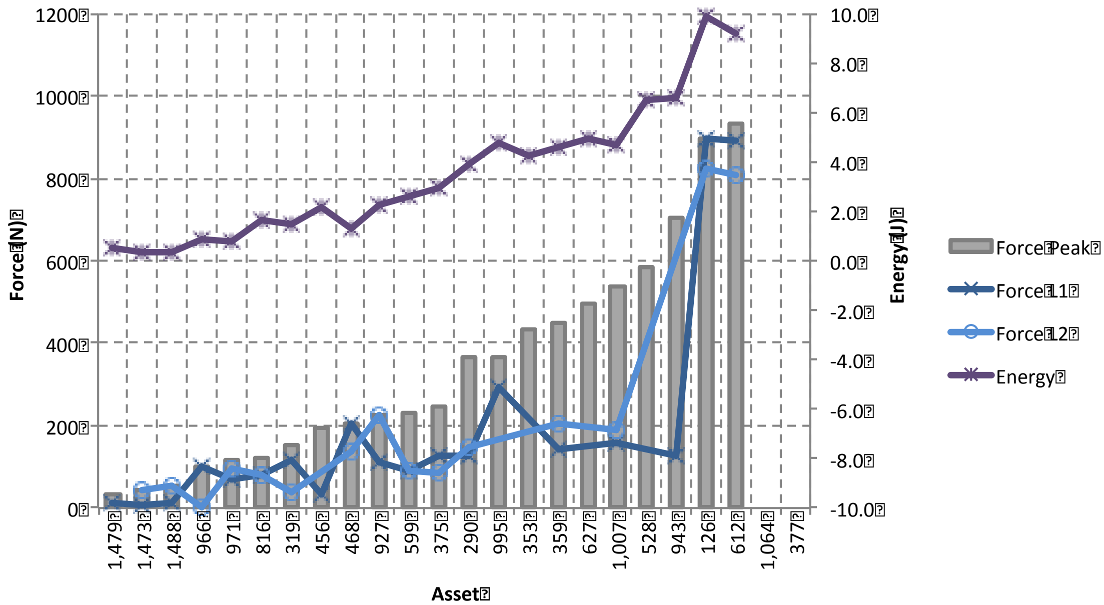

Figure 22: Push-through spiked weapon force test results.

It may be observed that the peak force corresponds well to the perforation forces of individual layers and that the energy also tracks in a similar fashion. These trends are not unexpected and provide a basis for further creating a weapon subset that eliminate relatively dull and underperforming weapons, i.e. where no perforation occurred or where high forces are involved. Further, it was of interest to see whether greater fabric deformation occurred at perforation due to the higher forces involved, however, no correlation between the weapon stroke, energy or peak force was observed.

The tip and edge sharpness performance results of the down-selected bladed and spiked weapons are presented in Figure 23 and Figure 24, respectively. The weapons are sorted by the peak force values noted earlier. No spike tip sharpness values were obtained for six weapons due to difficulty in performing the indentation test without significant bending of the weapon body.

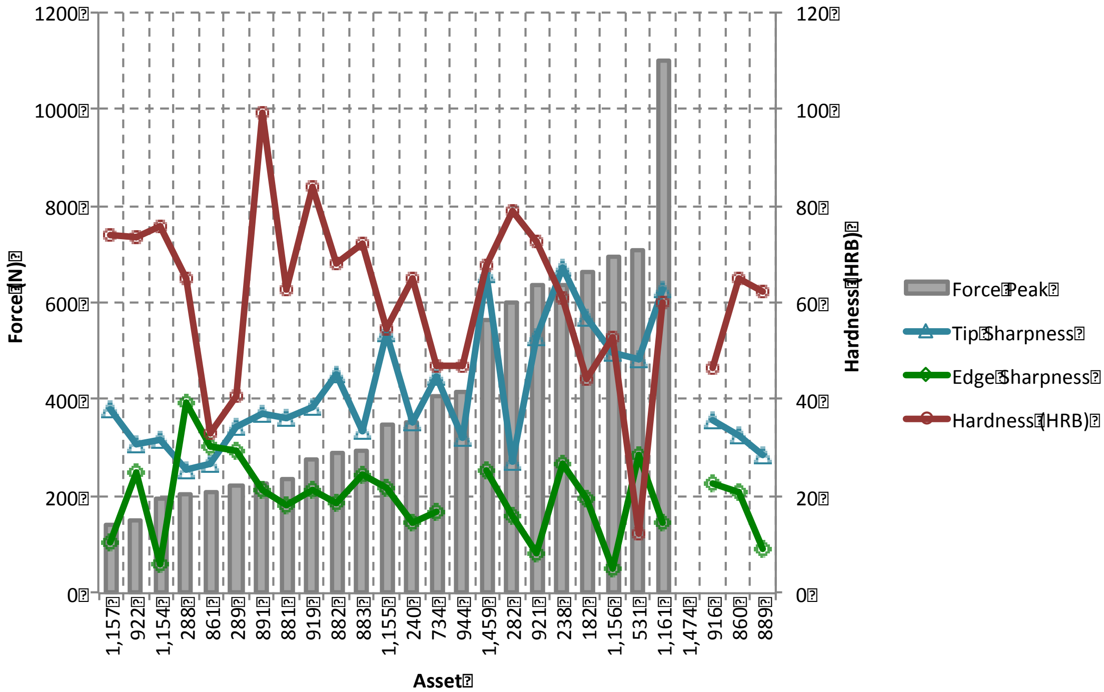

Figure 23: Push-through blade test performance and attributes.

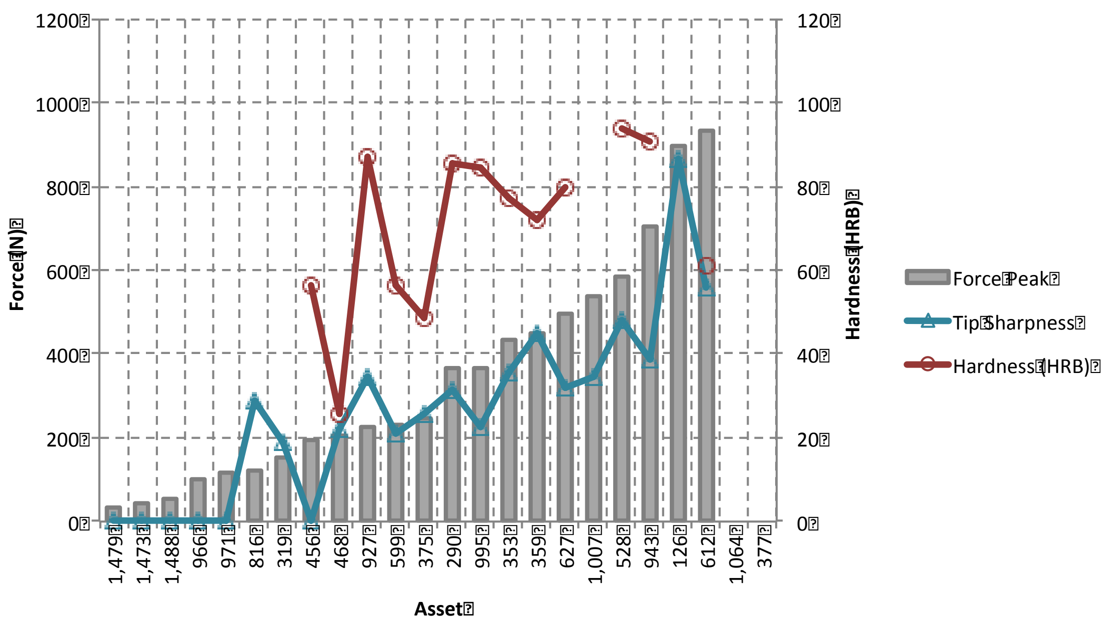

Figure 24: Push-through spike test performance and attributes.

The weapons with low peak forces tend to exhibit higher tip sharpness values (lower force) for both the blades and spikes. Edge sharpness for the blades did not correspond to peak force. Material hardness readings for the blades and spikes presented in the figures vary considerably and may be partly due to material composition, local hardness variations or weapon geometry leading to variable results.

The average of three hardness readings was reported to reduce these variations and has been used in the quoted results.

3.4 Exemplar Weapon Development

Based on analysis of the geometric and performance data shown, a subset of 9 bladed weapons and 9 spiked weapons were chosen for the further development of the exemplars. The purpose of the new subset was to identify weapons and their characteristics that were more aggressive. No stakes were chosen due to the small test sample size and overlapping performance with the other weapon types. The selected blades and spikes together represent 1.3% of the weapon survey.

The subset of 9 blade and 9 ice pick weapons are described in detail in Section 6.2 of the Biokinetics final report. Inspection of the bladed weapons showed that two distinctive styles were present; a double-edged symmetrical blade and a single edge single grind. Inspection of the spikes revealed two distinct styles, a small diameter short-coned style and a larger diameter, long coned style.

3.4.1 Buckling Modes

Assessment of the critical buckling loads was carried out during the initial weapon rankings in the taxonomy effort. The assumption of pivoting constraints at the tip and mid-handle was used and ranked weapons with more slender and longer blades or shaft poorly.

The Euler buckling mode was re-assessed and changed to a free-end constraint at the tip and fully constrained handle under the assumption that the bearer of the weapon can constrain the handle, Figure 25. This configuration also better represented the constrained condition with the NIJ 0115.00 weapon clamp. As a result, the critical loads for buckling with a free end constraint and full handle fixation were estimated assuming that steel was the base material and a constant cross sectional area. The results of the tests are presented in Table 13 and Table 14for bladed and spiked subset, respectively

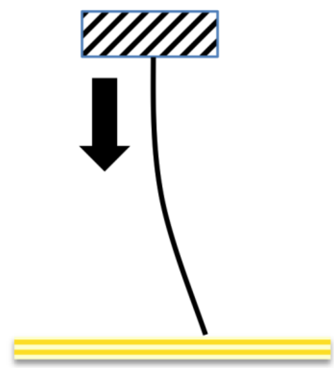

Figure 25: Buckling Mode

3.4.2 Flexural Stiffness

The amount of force required to displace the tip of the threat laterally was estimated for the bladed and spiked weapon subset. The calculations were based on the flexural stiffness of the weapon with the handle fixed and for a given side load, Figure 27. Steel was chosen as the base metal and a constant cross sectional area was used.

The flexural stiffness values for the blades are similar due to the similar cross sectional geometry while there were distinct differences for the spiked weapons, having greater cross sectional change due to variation in diameters. Experimental measurement of the actual flexural stiffness of the weapon subset was conducted. The test setup involved clamping the weapon letting it protrude 65 mm and applying a perpendicular force to the tip of the blade, Figure 28. The stroke of the load applicator rod was limited to 5 mm and a loading rate of 1 mm/s was used. The results of the tests are presented

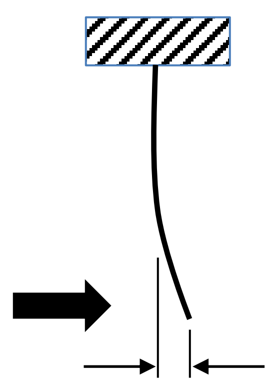

Figure 27: Flexural Stiffness

in Table 13 and Table 14 for the bladed and spiked subset, respectively. Measurements were not possible for some spikes with the current setup.

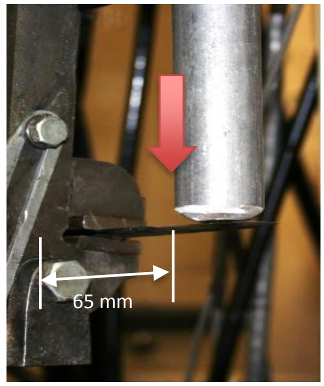

Figure 28: Experimental setup for flexural stiffness (courtesy of WSU).

3.4.3 Exemplar Materials

The materials used in the fabrication of the weapons varies significantly as observed from the hardness values, and corresponding yield strength, in Table 13 and Table 14 for the bladed and spiked weapon subset, respectively. The blade styles with double and single edges appear to have to different hardness values. The spiked weapons also appear to be of variable harnesses, however, there was little data for the selected subset of weapons and therefore an average of the 24 down selected spiked weapons was reported for the short-coned spike.

Table 13: Performance assessments of bladed weapon subset.

Asset	Performance									
	Buckle Load Est. Free (N)	Flexural Stiffness Est. (N/mm)	Flexural Stiffness Act.@65 mm (N/mm)	Force Peak (N)	Plateau Slope L1 (N/mm)	Energy (J)	Perf-oration (mm)	Tip Sharp-ness (N)	Edge Sharp-ness (N)	Hard-ness (HRB)
1157	1434	14	81	144	26	2.2	18	379	107	74
922	1792	22	55	152	23	2.4	18	308	251	74
1154	2245	24	48	195	16	2.7	25	315	61	76
288	1753	17	39	203	18	2.4	21	255	394	65
861	2730	29	48	211	40	2.3	14	267	302	33
289	1600	23	18	221	27	3.5	25	342	293	41
891	2685	40	83	228	13	2.6	14	372	215	99
881	2262	24	41	234	60	2.3	11	364	180	63
919	2577	36	13	278	41	3.3	18	385	214	84
Blade - Double Edged, Symmetrical										
Average	**2147**	**27**	**56**	**200**	**24**	**2.6**	**18.2**	**352**	**169**	**81**
Min	1434	14	13	144	13	2.2	14.0	308	61	74
Max	2685	40	83	278	41	3.3	24.5	385	251	99
SD	529	11	29	56	11	0.4	3.8	37	81	11
Exemplar (T2)	**2324**	**27**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**80**
Blade - Single Edged, Triangular										
Average	**2086**	**24**	**37**	**217**	**36**	**2.6**	**17.5**	**307**	**292**	**50**
Min	1600	17	18	203	18	2.3	10.5	255	180	33
Max	2730	29	48	234	60	3.5	24.5	364	394	65
SD	514	5	13	14	18	0.6	6.4	54	88	16
Exemplar (T1)	**1879**	**24**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**55**

Table 14: Performance assessments of spiked weapon subset.

Asset	Performance: Buckle Load Est. Free (N)	Flexural Stiffness Est. (N/mm)	Flexural Stiffness Act.@65 mm (N/mm)	Force Peak (N)	Plateau Slope L1 (N/mm)	Energy (J)	Perf-oration (mm)	Tip Sharp-ness (N)	Hard-ness (HRB)
1479	97	2.2	#N/A	32	#N/A	0.5	14	#N/A	#N/A
1473	202	9.1	#N/A	46	9	0.3	21	#N/A	#N/A
1488	27	0.4	#N/A	53	12	0.4	14	#N/A	#N/A
966	60	1.0	#N/A	101	#N/A	0.9	21	#N/A	#N/A
971	48	0.7	#N/A	116	8	0.8	14	#N/A	#N/A
816	781	10.6	#N/A	124	35	1.7	7	287	#N/A
319	#N/A	#N/A	17	155	58	1.5	14	190	#N/A
456	238	2.9	3	192	#N/A	2.2	21	#N/A	56
468	27	0.3	#N/A	206	58	1.3	21	222	26
Ice Pick - Short Taper									
Average	**87**	**2.7**	**#N/A**	**70**	**10**	**0.6**	**16.8**	**#N/A**	**70.6**
Min	27	0.4	#N/A	32	8	0.3	14.0	#N/A	#N/A
Max	781	10.6	17	206	58	2.2	21.0	286.6	#N/A
SD	69	3.6	#N/A	37	2	0	4	#N/A	#N/A
Exemplar (T3)	**191**	**2.7**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**68**
Ice Pick - Long Taper									
Average	**348**	**4.6**	**10**	**169**	**50**	**2**	**16**	**233**	**41**
Min	27	0.3	3	124	35	1	7	190	26
Max	781	10.6	17	206	58	2	21	287	56
SD	389	5.4	9	37	14	0	7	49	22
Exemplar (T4)	**344**	**4.9**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**68**

3.4.4 Exemplar Design

Development of the exemplar threats reflected the geometric and performance characteristics of the weapon subsets described by the averaged geometry of each style with adjustments made to the cross section at the clamped end to achieve similar buckling and flexural modes. Additional measurements of the blade grind depths were made from photographic data to determine the included angle of the edges. Since tip and edge radii could not be established from the surveyed weapon data measurements, the quasi-static performance data was relied upon for confirming the performance of the exemplars.

Four different exemplar threats were developed to represent the surveyed weapon styles:

Exemplar Designation	Description
T1	Blade: single edged, single grind, asymmetrically tapered with rectangular blade cross section.
T2	Blade: double edged, double grind, symmetrically tapered with rectangular blade cross section.
T3	Spike: small diameter rod, short tapered tip.
T4	Spike: medium diameter rod, long tapered tip.

The exemplar geometric specifications are given in the Biokinetics final report for the bladed and spiked exemplars, respectively. Varying degrees of tip and edge sharpness were investigated for each exemplar type in an attempt to determine the most representative attributes.

The bladed and spiked exemplar styles are depicted in Figure 29 through to 32. Engineering drawings can be found in Appendix D of the Biokinetics final report. Material selections have been proposed to achieve the correct hardness values, however, confirmation with the eventual weapon manufacturer is required.

Final specification of the tip and edge sharpness of the exemplars is required to best approximate the performance of the surveyed weapon subset. This is to be accomplished through quasi-static evaluations using the tip and edge indentation tests as well as the push-through tests.

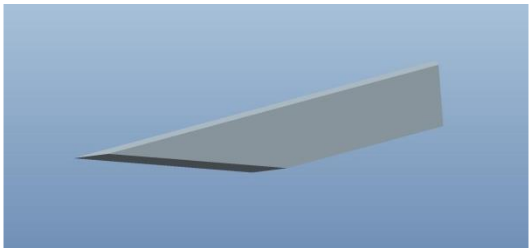

Figure 29: Blade exemplarT1

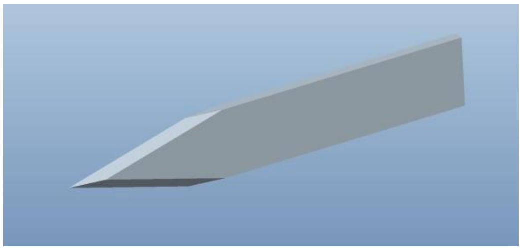

Figure 30: Blade exemplar T2

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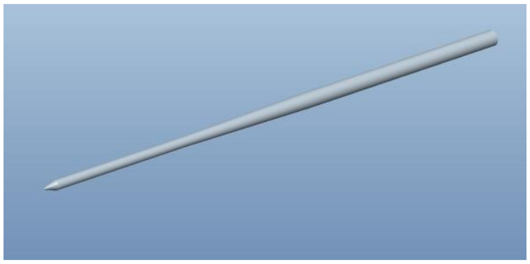


Figure 31: Spike exemplar T3

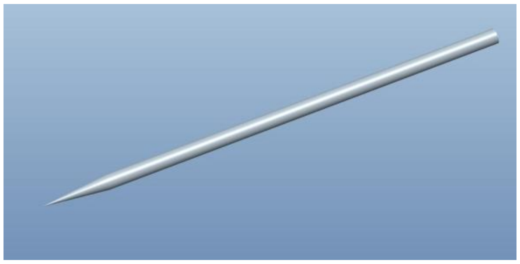


Figure 32: Spike exemplar T4

3.5 Exemplar Evaluations

3.5.1 Quasi-Static

The exemplars were evaluated to the same quasi-static tip sharpness, edge sharpness and push-through performance tests conducted for the survey weapon subset. The objective of the tests was to finalize the exemplar tip and edge sharpness based on the guidance provided by the tip/edge indentation results and the quasi-static push-through performance.

The four exemplar threat types (T1, T2, T3, T4) were to be tested in various configurations, each representing different degrees of tip and edge sharpness. The same exemplars used for the tip sharpness and edge sharpness tests were used for the push-through tests due to the non-destructive nature of the tip and edge indentation tests. Further, single tests were conducted with the exemplars to establish trends in the results while limiting the number of exemplars used.

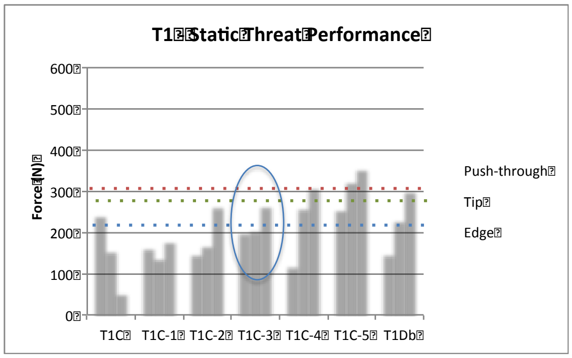
The quasi-static test results are provided in Table 15 and Table 16 for the blades and spikes, respectively, and graphically depicted in Figure 33. Table 15 and Table 16 and Figure 33 are taken from the Biokinetics final report.

Table 15: Quasi-static performance of bladed exemplars.

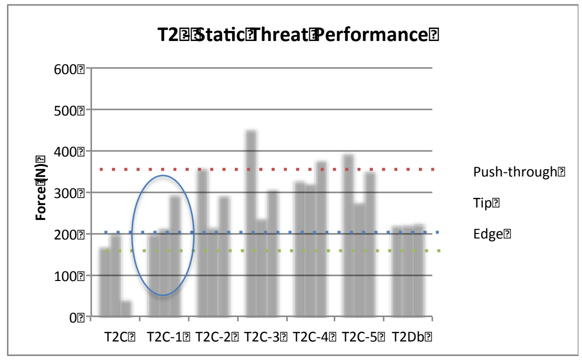
Asset	**Performance**									
	Buckle Load Est. Free (N)	Flexural Stiffness Est. (N/mm)	Flexural Stiffness Act.@65 mm (N/mm)	Push-through Force Peak (N)	Push-through Plateau Slope L1 (N/mm)	Push-through Energy (J)	Perf-oration (mm)	Tip Sharp-ness (N)	Edge Sharp-ness (N)	Hard-ness (HRB)
Exemplar (T1)	1879	24	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	55
T1C				243		2.4		156	54	
T1C-1				164		1.7		138	180	
T1C-2				148		1.6		170	264	
T1C-3				201		2.3		206	265	
T1C-4				119		1.5		260	310	
T1C-5				257		1.9		325	355	
T1Db				149		2.2		230	**301**	
Exemplar (T2)	2324	27	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	80
T2C				172		2.3		203	44	
T2C-1				203		2.3		217	297	
T2C-2				361		3.2		219	295	
T2C-3				455		4.2		240	310	
T2C-4				330		3.4		324	380	
T2C-5				396		4.2		279	354	
T2Db				224		2.8		225	227	

Table 16: Quasi-static performance of spiked exemplars.

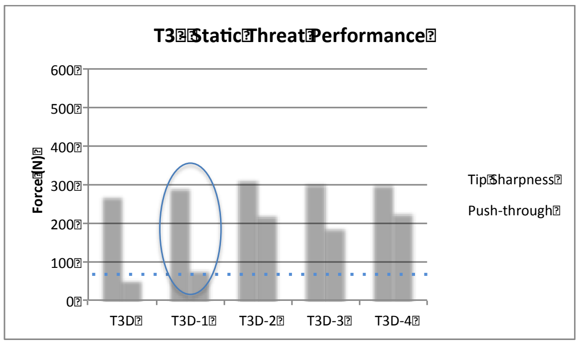
Asset	**Performance**								
	Buckle Load Est. Free (N)	Flexural Stiffness Est. (N/mm)	Flexural Stiffness Act.@65 mm (N/mm)	Push-through Force Peak (N)	Push-through Plateau Slope L1 (N/mm)	Push-through Energy (J)	Perf-oration (mm)	Tip Sharp-ness (N)	Hard-ness (HRB)
Exemplar (T3)	191	2.7	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	68
T3D				54		0.1		271	
T3D-1				80		0.2		293	
T3D-2				223		1.2		314	
T3D-3				189		0.7		304	
T3D-4				228		1.2		301	
Exemplar (T4)	344	4.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	68
T4C				164.9		**1.1**		73	
T4C-1				151.9		**1.3**		140	
T4C-2				160.5		1.4		199	
T4C-3				393.0		3.3		255	
T4C-4				508.2		0.0		278	



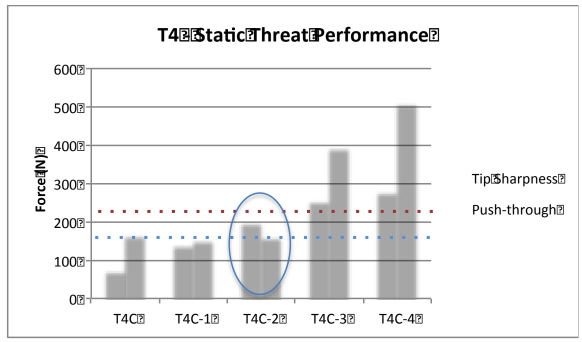
(a) T1 Exemplar



(b) T2 Exemplar



(c) T3 Exemplar



(d) T4 Exemplar

Figure 33: Quasi-static performance plots for the exemplars.

Comparison of the exemplar performance to the average survey weapon subset measurements can be made with the dashed lines in the figures. It may be observed that some variability of the exemplar threats exists with the tip, edge and push-through data for the different exemplars. However, for the spikes, a general trend can be seen where peak force increases as the tip sharpness levels deceased. Greater variability exists for the blades and is thought to be due to the additional armor interactions involving separation and cutting of the fibres. Additional testing is required to establish confidence bounds on the exemplar responses however this was outside the scope of the proposed program. Disparity between the exemplar tip/edge sharpness measurements and the averaged weapon were seen (Biokinetics final report). The reasons for this are not fully understood but are thought to be attributed to differences in surface finish, edge geometry, and test variability. Again, additional testing is required to establish the confidence bounds on the exemplar responses.

Selection of the appropriate sharpness levels was based primarily on the push-through results as the tip and edge forces did not always align with the push-through trends. The selected exemplars are presented in

Table **17**.

Table 17: Final exemplar specifications.

Type	Description	Notation
Blade	Single edged, asymmetrical	T1C-3
Blade	Double edged, symmetrical	T2C-1
Spike	Small dia., short taper	T3D-1
Spike	Med. dia., long taper	T4C-2

3.5.2 Dynamic Testing

The test methodology described by NIJ 0115.00 was used for the dynamic evaluation of exemplar threat performance. All exemplar tests were to be completed to the single energy level corresponding to the NIJ 0115.00 Level 3, E1 (43 J). The associated 7 mm penetration limit was used as the failure criterion for the current armor layer evaluation. In regards to armor selection, the number of layers were varied according to the requirements for the L_{50} determination.

A proposed test matrix is presented in Table 18. A total of 10 drop tests for each threat type is required to satisfy the L_{50} test methodology. New threats are used for each test and replacement of the backing materials, compression disks and witness paper follow the standard testing schedule of the NIJ 0115.00 standard.

Table 18: Test matrix for dynamic assessment of the exemplar threats.

Exemplar	Energy (J)	Armour Type	Layers*
T1C-3	43	Twaron Aramid SRM 509/930, loose layup	1-10
T2C-1	43	Twaron Aramid SRM 509/930, loose layup	1-10
T3D-1	43	Twaron Aramid Fabric - Microflex 60" (550 DTEX) Special HS, loose layup	1-10
T4C-2	43	Twaron Aramid Fabric - Microflex 60" (550 DTEX) Special HS, loose layup	1-10

* Note: The number of layers are determined during testing to achieve an equal number of pass/fail data points.

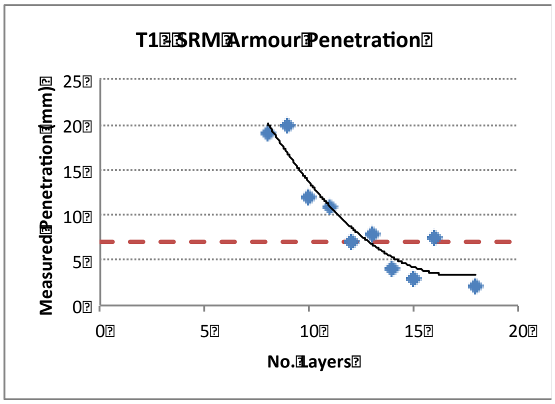
The dynamic performance summary of the bladed and spike threats are presented in Tables 29 and 30, respectively, of the Biokinetics final report. It may be noted that for the spike tests, not all 10 impacts were conducted due to damage to the threat holders from the threat striking the steel support plate located under the backing. The L_{50} assessment results are found in Table 19 below along with rudimentary statistics. The arithmetic mean and standard deviations are based on the selected number of layers used for the L_{50} assessments.

It may be noted that the required number of layers to meet the 7 mm failure criterion with a 50% risk level was the same for the two blades while the T3 blade was defeated with fewer layers of armor. Comparison of the two armor materials was outside the current scope of the program.

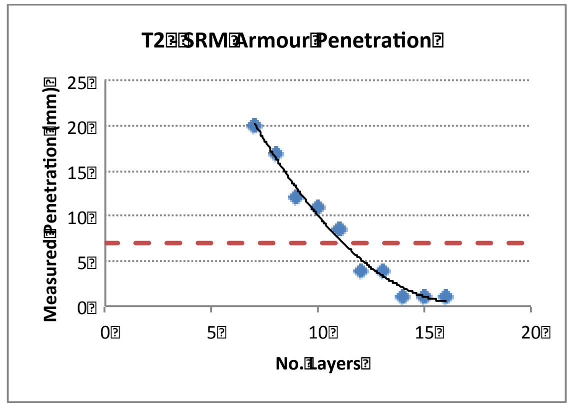
Table 19: L50 assessment for all exemplars.

Threat	Armour	L50 Mean	Low	High	Std. Dev.
T1C-3	Twaron Aramid SRM 509/930, loose layup	12	10	13	1.3
T2C-1	Twaron Aramid SRM 509/930, loose layup	12	9	14	1.9
T3D-1	Twaron Aramid Fabric - Microflex 60" (550 DTEX) Special HS, loose layup	5	3	6	1.3
T4C-2	Twaron Aramid Fabric - Microflex 60" (550 DTEX) Special HS, loose layup	7	5	8	1.3

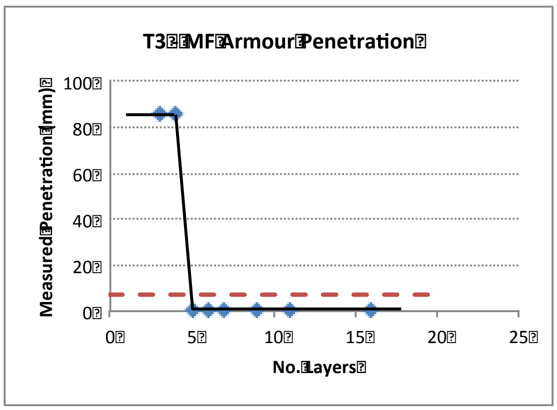
Depiction of the L_{50} test results are presented for the various exemplar threats in Figure 34. The 7 mm criteria is illustrated with a dashed line. Approximate trendlines are for illustrative purposes only.



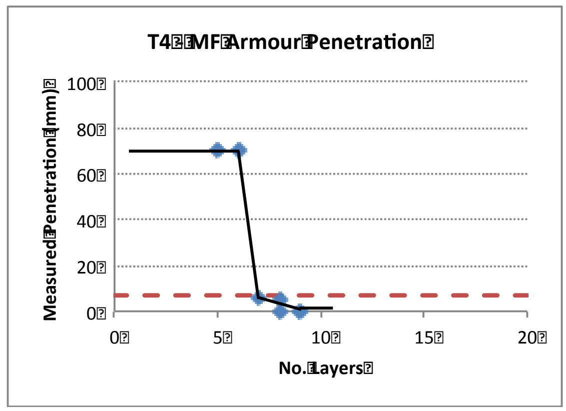
(a) T1 Exemplar



(b) T2 Exemplar



(c) T3 Exemplar



(d) T4 Exemplar

Figure 34: Dynamic test results of exemplar threats with various armor materials and layers.

4. Summary

4.1 Discussion of Findings

All the data from the current research was provided throughout the duration of the grant to the STC. A total of 1353 weapons were collected from over 20 facilities in the United States representing different prison types and security levels. Based on the weapons collected from these correctional facilities, two bladed and two spiked exemplar weapons were developed in order to achieve the ability to evaluate real-world threats. The presence of both threats may require an integrated approach for the development of stab resistant armor. Findings from the study are being considered for revision of the NIJ 0115 standard for assessing the stab resistance of body armor.

4.2 Implications for Policy and Practice

The overall goal of this research is to provide data to for the reassessment of the current NIJ 0115.0 Stab Resistant of Personal Body Armor. These data will help to serve the criminal justice community by focusing on an appropriate and sufficient level of protection for specific operational environments and helping to ensure that body armor is safe, effective, and performs as intended. Results of this research and data collection effort, as part of NIJ body armor standard revisions, will ultimately help to protect both law enforcement as well as correctional officers.

4.3 Implications for Further Research

Future work should include the ongoing assessment of any changes implemented into a revised standard. It is important that longitudinal data be collected to ensure that the threats remain relevant. Injury data should also be collected on an ongoing basis.

4.4 Conclusions

In summary, four exemplar weapons were developed to represent the threats found in correctional facilities and may be considered for future updates of relevant body armor performance standards such as NIJ 0115.00. The following findings and recommendations can be noted:

1. A stab weapon typology and taxonomy were successfully developed to identify potentially aggressive threats based on descriptive information,
2. Quasi-static performance tests were developed to characterize tip, edge and system performance for initial down-selection of stab weapons, however, additional work is required to establish confidence levels and potential for quality control measures of the exemplars,
3. Two bladed and two spiked exemplar weapons were developed from the geometric and performance characteristics of weapons obtained from correctional facilities in the US,
4. The proposed exemplars require a lesser number of armor layers to meet the current penetration limits of NIJ 0115.00 in comparison to the P1/A and S1/G exemplars,.
5. Greater use of the exemplars from the practitioners is required to fully understand their implications on armor design, relevancy and test variability.

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APPENDIX A

Different Types of Correctional Facilities within the United States of America

3.2 Different Types of Correctional Facilities within the United States of America

3.2.1 Main divisions:

Type of Facility	Security Level		
Federal	Low	Medium	Max
State	Low	Medium	Max
Tribal Prison	Facilities general house all security levels		
Youth offenders	Facilities general house all security levels		

3.2.2 Federal Prison Security level Breakdown

Minimum security institutions: also known as Federal Prison Camps (FPCs), have dormitory housing, a relatively low staff-to-inmate ratio, and limited or no perimeter fencing. These institutions are work and program oriented.

Low security Federal Correctional Institutions (FCIs) have double-fenced perimeters, mostly dormitory or cubicle housing, and strong work and program components. The staff-to-inmate ratio in these institutions is higher than in minimum security facilities.

Medium security FCIs have strengthened perimeters (often double fences with electronic detection systems), mostly cell-type housing, a wide variety of work and treatment programs, an even higher staff-to-inmate ratio than low security FCIs, and even greater internal controls.

High security institutions, also known as United States Penitentiaries (USPs), have highly secured perimeters (featuring walls or reinforced fences), multiple- and single-occupant cell housing, the highest staff-to-inmate ratio, and close control of inmate movement.

Federal Correctional Complexes (FCCs), institutions with different missions and security levels are located in close proximity to one another. FCCs increase efficiency through the sharing of services, enable staff to gain experience at institutions of many security levels, and enhance emergency preparedness by having additional resources within close proximity.

Administrative facilities are institutions with special missions, such as the detention of pretrial offenders; the treatment of inmates with serious or chronic medical problems; or the containment of extremely dangerous, violent, or escape-prone inmates. Administrative facilities include Metropolitan Correctional Centers (MCCs), Metropolitan Detention Centers (MDCs), Federal Detention Centers (FDCs), Federal Medical Centers (FMCs), the Federal Transfer Center (FTC), the Medical Center for Federal Prisoners (MCFP), and the Administrative-Maximum Security Penitentiary (ADX). Administrative facilities, except the ADX, are capable of holding inmates in all security categories.

3.2.3 State Prison System Breakdown

County jails are used primarily to hold defendants during court proceedings and those who have been sentenced to a period of less than a year.

State prisons usually house people who have been found guilty of state felonies and are sentenced to prison to serve a year or more. (State prisons are also sometimes referred to as “penitentiaries,” “correctional institutions,” “reformatories,” “detention centers,” or “work camps.”)

Major Institutions - Large facilities that generally house medium to maximum security inmates. These institutions provide medium security dormitory-style living areas for non-disruptive inmates, celled close security living areas for non-disruptive inmates with long sentences, and celled maximum custody living areas for inmates with severe behavior problems, extremely long sentences or predatory type behavior

Correctional Units - Small facilities that house minimum and medium security inmates in dormitory-style living areas. Inmates must demonstrate non-disruptive behavior. These units do not house inmates convicted of homicide, kidnapping/abduction, violent sex offenses or those determined to be escape risks

3.2.4 Security level descriptions and prisoner classification

Security level descriptions and prisoner classification differ slightly from state to state, but as a general guide, below described is the classification system for Virginia Department of Correction on determining what security level

Security level 1 Low - No Murder I or II, Robbery, Sex-related crime, Kidnap/Abduction; Felonious Assault (current or prior), Flight/Escape; Carjacking; Malicious Wounding; Assault/Flight/FTA pattern; No Escape Risks; No Felony Detainers; No Disruptive Behavior.

Security level 1 High - No Murder I or II; Sex offense, Kidnap/Abduction, Escape History. No Disruptive Behavior for at least past 24 months.

Security level 2 - No Escape History within past 5 years. Single Life sentences must have reached their Parole Eligibility Date (PED). No disruptive behavior for at least past 24 months prior to consideration for a transfer to any less-secure facility.

Security level 3 - Single, multiple, & Life + sentences must have served 20 consecutive years on sentence. No disruptive behavior for at least past 24 months prior to consideration for a transfer to any less-secure facility

Security level 4 - Long Term; Single, multiple, & Life + sentences. No disruptive behavior for at least past 24 months prior to consideration for a transfer to any less-secure facility.

Security level 5 - Long Term; Single, multiple, & Life + sentences. No disruptive behavior for at least past 24 months prior to consideration for a transfer to any less-secure facility.

Maximum Security - Long Term; Single, multiple, & Life + sentences. PROFILE: Disruptive; Assaultive; Severe Behavior Problems; Predatory-type behavior; Escape Risk.

APPENDIX B

Weapon Data Entry

1.1.1.1 : Weapon Data Entry Table

Sample contents of worksheet: “Data Entry Spreadsheet for Weapon Characterization BioK V40.xlsx”.

		Asset Type				Tip				
						Description		Geometry and Material		
	Phase	Agency Type	Overall Length (mm)	Overall Weight (g)	Style	Tip Material	Tip Shape Description	Tip Radius (mm)	Tip Cone (deg)	Spike Diameter (mm)
	I - Typology	X	X	X	X	X	X		X	X
	II - Effectiveness	X	X	X	X	X	X	X	X	X
	III - Exemplar Development	X	X	X	X	X	X	X	X	X
Typical minima - maxima, criteria or descriptors used for error checking via Excel Condiitonal Formatting			10 450	1.0 500.0	blade ice pick slash stake	metal plastic wood glass	pointed curved square chiseled round		2.0 180.0	1.00 20.00

Edge			Blade/Body							Handle		
Description		Geomet	Description							Description		
Edge Condition	No. Edges	Edge Grind Sides, Edge No. 1	Blade Material	Blade Shape - planar	Blade Spine	Blade Serrations (describe)	Blade Width (mm)	Spike Diameter (mm)	Blade Thickness (mm)	Handle Length (mm)	Handle Tang	Handle Guard
X	X		X	X	X	X	X	X	X	X	X	X
	X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X		
sharp blunt serrated blunt serrated sharp	0 1 2	0 1 2	metal plastic wood glass	sym sqr rnd trg serrated	no yes	none top bottom both	0.5 66.0	"=Col T	0.5 15.0	40 500	none partial full	none yes

											Performance Evaluation		
											Description		
Armour System Description	No of Aramid Layers Weapon Perforated	Perforation (mm)	Stroke at Peak (mm)	Stroke L1 Start (mm)	Stroke L1 End (mm)	Force L1 Start (N)	Force L1 End (N)	Plateau Force L1 - slope (N/mm)	Stroke L2 Start (mm)	Stroke L2 End (mm)	Force L2 Start (N)	Force L2 End (N)	Plateau Force L2 - slope (N/mm)
X	X	X	X	X	X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X	X	X	X	X	X
make model etc													

Stroke L3 Start (mm)	Stroke L3 End (mm)	Force L3 Start (N)	Force L3 End (N)	Plateau Force L3 - slope (N/mm)	Peak Force (N)	Energy (J)	Failure Mode; Armour	Un-fair Test
X	X	X	X	X	X	X	X	X
X	X	X	X	X	X	X	X	X
							retention cutting firbre separation	threat premature failure threat slippage armour slippage sensor failure etc

Asset Characteristics				
Quasi-static Test Sample (Y/N)	Tip Test Max Force (N)	Edge Sharpness (N)	Hardness	Flexural Stiffness (N/mm)
X	X	X	X	X
X	X	X	X	X

APPENDIX C

Weapon Data Entry – Completed Data BaseTables

Appendix C - Data
Entry Spreadsheet for

APPENDIX D

Final Report of Biokinetics and Associates Ltd

R13-11 Char of
Weapons Stab - Ph II

APPENDIX E

Accepted Paper

Development of Stab Weapon Exemplars from a Survey of Threats in a Corrections Environment

To be presented at Personal Armour Systems Symposium, Sept 8-12, 2014, Cambridge, UK

Appendix E -
Shewchenko - Develo

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