Development and validation of knee and elbow guards for combined ballistic and impact protection

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Abstract. Traditional knee and elbow guards used in the military are worn over garments and only offer impact protection. Often, these guards are secured to the joint using adjustable straps. As such, these guards are bulky and difficult to keep in position over the joint, especially during high-mobility activities like running and jumping. In addition, there can be substantial abrasion, chaffing and perspiration associated with prolonged usage of the protector over the joint. The objective of this work is to illustrate the development and validation of a low profile, multi-threat, knee and elbow guard system that specifically provides protection against impact, projectiles, ballistic threats and blast fragmentation debris, while remaining compatible with existing combat uniforms and equipment. Two distinct solutions have been designed, one meeting more stringent protection requirements, and a lighter and less bulky version meeting lower level protection requirements still deemed of relevance to military activities. Various reference standards were used to justify a minimum level of appropriate protection from fragmentation and from impact, relative to the application. For fragmentation, an analysis of Improvised Explosive Devices threats was used to determine relevant and realistic protection targets. For impact protection, significant efforts were first devoted to identifying appropriate test methodologies to adopt, in view of multiple existing standards from sports and other civilian applications. Drop tower impact attenuation tests were then conducted to optimize the protection provided through the selection of innovative dual-purpose materials. Finally, a limited set of human factors trials was organized, focusing on quantifying the potential benefits of the lighter-weight version in terms of flexibility, comfort and functionality, based on early prototypes built in various sizes. This work resulted in the development of promising fully functional prototypes ready for larger scale human factors evaluation and eventual production.

1. INTRODUCTION

Blast-related injuries from improvised explosive devices (IEDs), land mines and shrapnel predominate battlefield injuries, with approximately 70% these occurring to the upper and lower extremities [1,2,3]. Personal Protective Equipment (PPE) worn over the torso often leaves arms and legs unprotected. Traditional knee and elbow guards used in the military do not protect against blast debris and only offer impact protection or comfort when kneeling in rough terrain. Often, these guards are worn over garments and secured in place using adjustable straps with buckles or Velcro. They are bulky and difficult to keep in position over the joint, especially during high-mobility activities like running and jumping. In addition, there can be substantial abrasion, chaffing and perspiration associated with prolonged usage of the protector over the joint.

The goal of this work is to illustrate the development and validation of a low-profile knee and elbow guard system offering multi-threat protection against impact, ballistic threats and blast fragmentation, while remaining compatible with existing combat uniforms and equipment. Towards this goal, reference standards were first reviewed to justify a minimum level of appropriate protection from impact and from fragmentation. For impact protection, these included standards for knee protection in sports and civilian workplace settings. For fragmentation, an analysis of Improvised Explosive Devices (IED) threats from Defence R&D Canada – Valcartier (DRDC) was used to determine relevant and realistic protection targets. With a test methodology selected, a rigorous set of drop tower impact attention tests was then conducted to optimize the protection provided through the selection and stacking of innovative materials. Finally, limited human factors trials were completed focused on understanding the user requirements for flexibility, comfort and functionality.

Figure 1: Prototype Knee Protection – Version 1 (Left, higher protection level) and Version 2 (Right, lower protection level)

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Two solutions have been designed as shown with the knee version in Figure 1. Both solutions were worn next to skin and used a compression tube to secure the garment over the joint. Version 1 met more stringent protection requirements while Version 2 was lighter and less bulky, meeting lower level protection requirements still deemed of relevance to military activities. The development for both solutions reached a stage where promising fully functional prototypes are ready for larger scale human factors evaluation and eventual production.

2. BACKGROUND

A market review of available protective ballistic and non-ballistic knee and elbow guards identified best practices in design and material selection. Traditional combat knee and elbow guards typically feature rigid outer shells and are cumbersome and difficult to keep in place. They are worn over garments and only offer impact protection. Some tactical trousers now include knee pads integrated into the garment. In sports, like biking, skating, baseball and soccer, the trend is towards soft armour worn next to skin. These compression garments are lighter and more flexible than traditional equipment. Some examples of each are presented in the following sections.

Non-ballistic knee and elbow guards may be issued to soldiers as part of their kit or purchased by soldiers by their own initiative. They offer impact protection but do not protect against ballistic or fragmentation threats. Many major retailers of combat gear for military or police use offer such traditional knee and elbow guard solutions. While the appearance varies, most models use a similar construction of a foam backing with a rigid plastic outer shell, with straps to secure the guard to the knee or elbow joint. In the Canadian Armed Forces, knee protection has been designed into the new Improved Combat Uniform (ICU) combat pant via an exterior pocket positioned over the knee to accommodate a removable, foam knee pad. The uniform does not include integrated elbow pads, but traditional tactical elbow and knee guards are available to wear over the uniform. The UK military kit includes a standard tactical knee pad that is worn over the trouser but does not include elbow pads. The US Army Combat Pant (ACP) has integrated, removable hard-shell knee pads. Traditional knee and elbow pads are also available. The US Army combat shirt features elbow pads, but these are for abrasion resistance only, i.e. they prolong the life of the shirt.

One ballistic knee guard was found during this market research. It is offered by TACARM Tactical Armor (www.tacarm.com) and claims ballistic protection to NIJ Level IIIA. This guard is a traditional tactical construction with the addition of a pocket that can hold one or two ballistic inserts (depending on the desired protection level) constructed from an aramid material.

Recreational guards for sport often mimic the design of tactical guards. For active sports where keeping the guards in place is the priority, traditional straps are replaced by a compression sleeve to secure the guard, but these must be worn directly against the skin. These lightweight, flexible guards use rate-dependent impact attenuating materials sewn directly to the compression sleeve. To maintain comfort and flexibility, a rigid outer shell is avoided. G-Form (g-form.com) has several such products that differ in the coverage and performance of the impact attenuating material. In addition to knee and elbow guards, G-Form also offers shirts, shorts, and shin and ankle guards.

Work knee pads may be used in recreational (e.g. home gardening) or professional (e.g. construction) contexts. Again, the design of these guards is like that of tactical guards but with an emphasis on comfort for working in the kneeling position over extended periods. Work knee pads often use thicker, more compliant foam, forego the rigid outer shell but still use straps to secure the guard. BlakLader (www.blaklader.uk), a manufacturer of work wear, takes an alternate approach to providing knee protection by including a kneepad pocket in their trousers. They offer different grades of kneepads but none that can be worn without the trouser. Elbow pads are not commonly available in this working category.

3. PERFORMANCE STANDARDS

The knee and elbow guards developed for the current application are meant to provide both impact and fragmentation protection. While there is some consensus on which test methodology to use to evaluate fragmentation and ballistic protection performance (e.g. V50 rating [4]), there is a wide range of test methodologies addressing blunt impact mitigation, making the selection of a specific test methodology challenging.

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3.1 Description

Performance standards related to impact of the knee and elbow are presented in Table 1. The intended use upon which each standard is developed is listed. Some examples of products discovered during the market research claiming compliance to these standards are also shown. The above listed performance standards involve similar test methodologies in that the test apparatus consists a guided mass falling onto the test specimen placed on an anvil. The impactor and the anvil differ somewhat amongst the standards in material, shape and weight, with some anvils including a complex curvature to better accommodate the knee and elbow guards. Impact velocity and transmitted force are typically measured. The drop height of the impactor is prescribed in order to meet the required impact energy of the given standard. It should be noted that these standards are not limited to impact protection, and often include requirements related to sizing, coverage, ergonomics and restraint. The impact energy and allowable transmitted force for each standard are listed in Table 2. Note that many of these standards feature more than one performance level.

Table 1: Performance Standards for Knee and Elbow Guards

No.	Title	Use
EN 15613	Knee & Elbow Protectors for Indoor Sports [5]	Light Falls
EN 1621-1	Motorcyclists' Protective Clothing against mechanical impact [6]	Hard Falls, Abrasion
EN 14120	Wrist, Palm, Knee & Elbow Protectors for Users of Roller Sports Equipment [7]	Light Falls
EN 14404	Personal Protective Equipment – Knee Protectors for Work in the Kneeling Position [8]	Working Position
EN 7971-4	Protective Clothing in Violent Situations [9]	Blunt Impact
CSA Z617-06	PPE for Blunt Trauma [10]	Blunt Impact

Table 2: Thresholds for Performance Standards

Standard	Level	Impact Mass (kg)	Elbow		Knee	
			Impact Energy (J)	Transmitted Force (kN)	Impact Energy (J)	Transmitted Force (kN)
EN 15613	A	2.5	1	4	2.5	6
	B	2.5	1.5	4	4	6
EN 1621-1	1	5	50	35	50	35
	2	5	50	20	50	20
EN 14120	1	5	6	4	12	6
	2	5	15	4	25	6
EN 14404	N/A	2.5	N/A	N/A	5	3
EN 7971-4	1	5	N/A	N/A	5	10
	2	5	N/A	N/A	15	10
	3	5	N/A	N/A	30	10
CSA Z617-06	N/A	1.46	15	3	20	3

3.4 Comparison Methods

Determining the relative severity of these knee and elbow guard performance standards was not possible by solely plotting input impact energy versus allowable transmitted force. Meeting the performance threshold for a given standard is influenced by the accumulated differences of apparatus, methodology and interpretation of results [11]. Two alternate ranking methods were explored, referred to as "Compression Distance" and "Contact Time", based on conservation of energy and momentum, respectively.

In the first comparison method, it is assumed that the impactor mass will induce a triangular force load on an infinitely thick material specimen (see Figure 2). The height of the triangle is based on the maximum allowable force threshold (F) from the specific standard, and the energy of the impact (E) corresponds to the area under a force-distance curve, as described in Equation 1. This equation can

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then be re-arranged to solve for the distance (d), as shown in Equation 2. The performance standards were then ranked where a greater distance, d, indicated a higher severity impact.

$$E = {}^{1}/_{2}\,Fd \tag{1}$$

$$d = \frac{2E}{F} \tag{2}$$

The second comparison method was based on the conservation of momentum, using impactor contact time as the comparator. Here, the linear momentum was computed using the velocity (v) and the prescribed mass (m) of the impactor, as shown in Equation 3, and equated to a term involving the maximum allowable force threshold (F). Finally, the contact time (t), i.e. the time required by the material specimen under test to absorb the load, was calculated by dividing the momentum by the performance standard's threshold of transmitted force, shown in Equation 4. The performance standards were then ranked based on a longer contact time indicating a higher severity impact.

$$F\,t = m\,v \tag{3}$$

$$t = \frac{mv}{F} \tag{4}$$

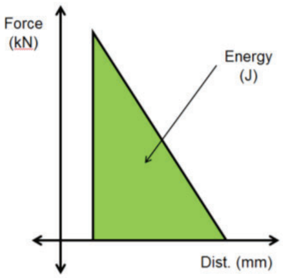

Figure 2: Idealized triangular force (F) versus distance (d) loading, with energy (E) represented as the area under the curve

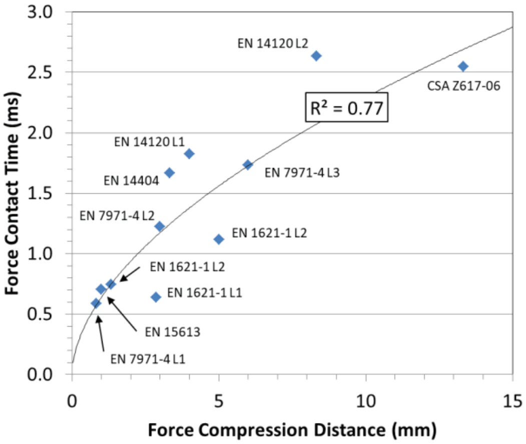

Figure 3: Force Contact Time vs. Force Compression Distance

3.5 Ranking by Test Severity

The estimated force contact time is plotted against the force compression distance, as shown in Figure 3. The R^2 value indicates a strong agreement between the two ranking methods. The computed values were used only to rank the severity levels and not meant to quantify a difference in severity. That is, twice the compression distance does not necessarily equate to twice the severity, or the amount of protection required is doubled, for example.

Given that both ranking methods correlated well to each other, the force compression distance method was arbitrarily selected to list the standards from most to least severe in Table 3. The rank number from the force contact time is also shown and is often near the distance rank value. A method to combine the ranking methods to establish an overall severity ranking was not developed nor applied.

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Table 3: Overall Ranking of Performance Standards by Severity (most to least severe)

Standard		Level	Compression Distance Rank	Contact Time Rank
No.	**Title**			
CSA Z617-06	PPE for Blunt Impact	N/A	1	2
EN 14120	Protection for Roller Sports	2	2	1
EN 7971-4	Protective Clothing in Violent Situations	3	3	4
EN 1621-1	Motorcycle Protective Clothing	2	4	7
EN 14120	Protection for Roller Sports	1	5	3
EN 14404	Work in a Kneeling Position	N/A	6	5
EN 7971-4	Protective Clothing in Violent Situations	2	7	6
EN 1621-1	Motorcycle Protective Clothing	1	8	10
EN 15613	Protection in Indoor Sports	B	9	8
EN 7971-4	Protective Clothing in Violent Situations	1	10	9
EN 15613	Protection in Indoor Sports	A	11	11

For a given standard with more than one protection level, the two suggested ranking methods were found to have properly sorted the implied severity of each of those levels. The rankings were also found to align with severity expectations based on the intent of the standard, i.e. equipment for indoor sports is low on the list while riot gear is more severe.

With this information available, the next task consisted in selecting the most appropriate test methodology. Towards that end, former members of the Canadian Forces among Med-Eng staff identified the primary functions of the knee and elbow guards to be comfort and protection from abrasion resulting from normal activities like working in a kneeling position or lying prone on the ground. It was determined that the impact protection levels need not be equivalent to personal protective equipment designed for severe falls or motor vehicle incidents.

As such, the EN 14404 standard for working in a kneeling position was selected, as its intent was deemed representative of the product use, and the impact test severity ranked in 6th place with the distance method and 5th in the time method out of the 11 performance levels. Since it is neither the most nor least severe test, it was deemed suitable for evaluating material options in the current study. Unfortunately, this standard did not address elbow guards so it was decided that the protection level afforded to the knee joint with the novel knee guard would be applied to the elbow area as well.

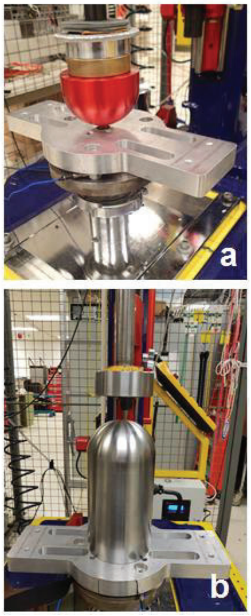

Figure 4: Impact test set-up for Phase 1 (a) and Phase 2 (b)

4. IMPACT TESTING

With the blunt impact test methodology selected, impact attenuating materials of different thickness, grade and type were then combined and subjected to impact testing to guide material selection for the construction of prototype knee and elbow guards.

4.1 Test Method and Set-up

Impact tests were subdivided into two phases. The first phase was conducted using a flat force plate impacted with a large hemispherical impactor. This flips the methodology called for in the second impact test phase in the selected EN 14404 test method, whereby a nearly-flat, shallow curved impactor strikes a hemispherical anvil placed on a force plate. Tests were conducted in this order to accommodate the available flat samples of raw materials. Moreover, test results from the Phase 1 were considered alongside areal density and material availability to select specific samples for testing in Phase 2. Details of each test set-up as well as photos are provided in Table 4 and Figure 4, respectively.

In both test configurations the desired impact energy was 5 J and the drop height was adjusted to compensate for losses in the measured impact velocity due to friction in the guided drop tower. Also measured was the impact force using three force sensors

(PCB Piezotronics 208C05) arranged to support the static force plate. Each of the three force sensor signals was post-processed using a CFC600 filter attenuating signals above 1000 Hz and then directly summed to create a single transmitted force, from which a peak value was extracted. The peak value was then normalised with respect to the calculated energy input from the velocity measurement at moment of impact.

Table 4: Impact Test Methods

Set-Up	Method	Force Plate	Impactor	Impactor Mass (kg)	Drop Height (cm)
1	Custom	Flat	Curved	1.04	55
2	CS EN 14404	Hemispherical	Flat	2.56	21

4.2 Test Results

A total of 225 flat sample tests were conducted on 75 variants created by selecting materials from 48 different material options prior to selecting the top performing candidates for the EN 14404 hemispherical testing.

Phase 1 testing had two goals. The first goal was to determine the effect of soft ballistic materials on the impact performance of impact attenuating material, and the second was to characterize materials that were available in different densities. To address the initial goal, two impact materials were selected for impact tests conducted with layers of different ballistic materials with areal densities ranging from 0.64-2.88 kg/m^2. After normalising the transmitted force with respect to trials without any ballistic material, it was found the ballistic material had little to no effect on the transmitted force (see Figure 5), with the vast majority of data points lying within 10% of the average values. This result thus allowed the selection of ballistic material to be based solely on user comfort and known ballistic performance.

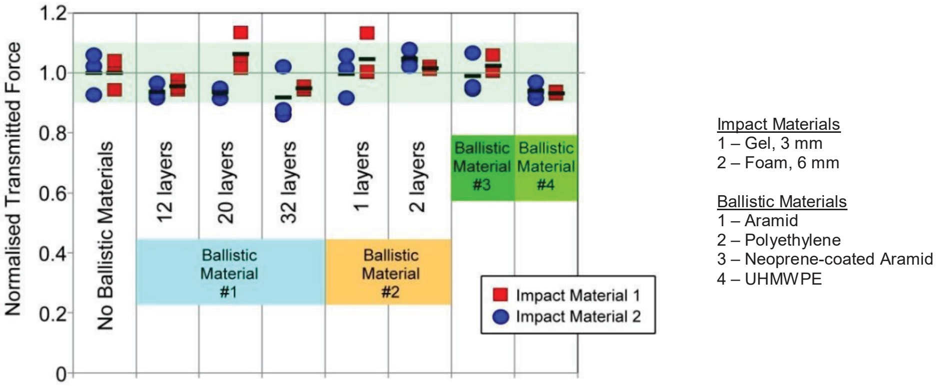

Figure 5: Normalised transmitted force of the two different impact materials using seven different ballistic material options

Towards the second goal of characterizing the performance of potential impact attenuating materials, four different low-density polyethylene and polyurethane foams were used. The low-density polyethylene and polyurethane foams were labelled LDPE-1 to LDPE-4 and PU-1 to PU-4, respectively, representing increasing densities of available foams. Figure 6 illustrates how the two types of impact foams diverged significantly under the chosen loading. The low-density polyethylene foams showed little sensitivity in transmitted force within the chosen density range, as it yielded a strong correlation with the foam thickness. In comparison, the polyurethane foams showed far greater sensitivity to density, whereby the sample thickness played a substantially lesser role.

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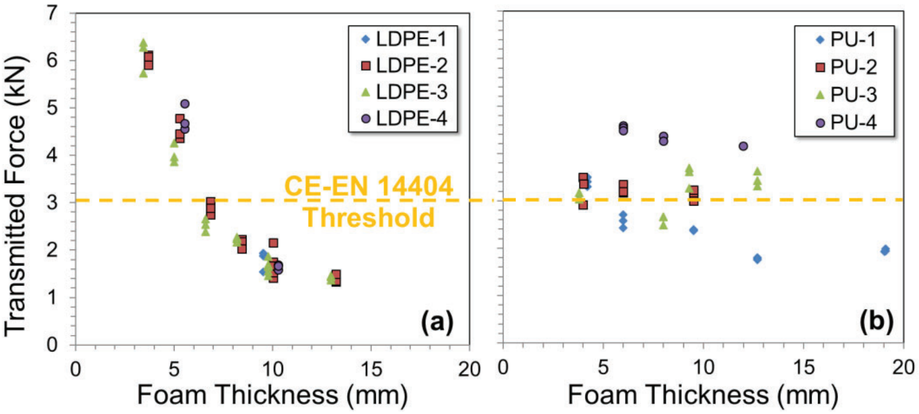

Figure 6: Transmitted force plotted with respect to (a) low-density polyethylene and (b) polyurethane foam thickness for the four different foam densities

After the flat sample Phase 1 testing was completed, 23 novel variants were tested using the Phase 2 EN 14404 hemispherical set-up, alongside 10 commercially available products to establish a baseline level of performance. The results are shown in Figure 7 with only the three best performing novel variants included. Many of the commercially available products reduced the transmitted force to within the threshold of the performance requirement while most of the proposed guards did not. This was due to the semi-rigid outer shell used on the commercially available products to distribute the load across a greater area, whereas the novel guards used only compliant materials aiming to improve comfort and flexibility for the user. Of the novel variants downselected options from Phase 1, only two passed the EN threshold in Phase 2 testing. The top performer was then selected for use in the first prototypes of the knee and elbow guards.

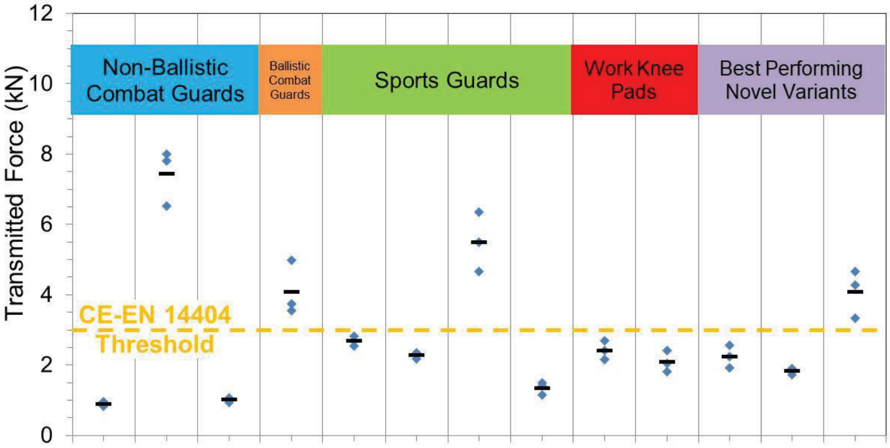

Figure 7: Transmitted force of the commercially available samples and downselected options

5. BALLISTIC PROTECTION

The three downselected options from Phase 2 tests utilised the same felt material to provide ballistic protection, a multi-layer composite fabric of aramid and ultra-high-molecular-weight polyethylene (UHMWPE). This felt was then used to construct the first prototype knee and elbow guards. A neoprene-coated aramid was selected to provide a durable surface to the front, outside of the guards. Finally, a stretchy polyethylene knit fabric was used in the construction of the compression tube that secures the garment over the joint. The V50 ballistic rating [12] with a 17-grain Fragment Simulating Projectile (FSP) was 404 m/s. It was previously shown that the extra ballistic layers would not greatly affect the impact performance. As such, impact testing on the complete ensemble was not deemed necessary.

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6. HUMAN FACTORS EVALUATIONS

Prototype knee and elbow guards built from materials selected based on their fragmentation and impact protection performance, were evaluated with human subjects for fit and protective coverage across multiple sizes and for effects on mobility through the completion of a rigorous obstacle course.

6.1 Sizing Study

A sizing study with 22 participants recruited from the Med-Eng workforce was completed to validate the pattern sizing and assess overall fit. This sample size is comparable to the test panel of 25 participants recommended for evaluating first responder protection against chemical, biological, radiological, and nuclear (CBRN) events [13]. The participants in this study did not have military experience and were recruited solely for anthropometric comparison. Body measurements of each participant included circumference of the bicep, elbow and forearm (for the elbow guard) and thigh, knee and calf (for the knee guard). Three females and 19 males participated with body mass and stature ranging from 61-98 kg and 159-197 cm, respectively.

Three sizes (small, medium and large) of the more protective Prototype Version 1 were available for fitting and each participant selected the best fit after trying each size. Participants were also invited to comment on fit issues including bunching (too much material gathering on inside of joint), cuffs (tightness relative to overall guard), grading (difference from one size to the next) and length (coverage over joint). The results of the sizing study drove changes implemented in design, pattern and grading for the Prototype Version 2.

6.2 Mobility Test

A mobility test was conduced to assess how the knee and elbow guards might affect a soldiers' ability to complete typical combat activities. The CAN-LEAP (CANadian Load Effects Assessment Program) combat mobility course provides sequential activities representing common and physically challenging tasks encountered by soldiers [14]. It includes standardized running, climbing, crawling and weapon-related activities to characterize the effect of soldier equipment on the soldiers' mobility. However, the use of CAN-LEAP was beyond the scope of the current study but may be used in future work. Instead, an abbreviated obstacle course was created to replicate the movements necessary by a soldier to complete the CAN-LEAP course, with an emphasis on activities involving the knees and elbows. Since the CAN-LEAP course is often set-up indoors on a concrete floor, two weapons activities were added that placed the participants' knees and elbows into a tray of 6 mm gravel to evaluate comfort over simulated rough terrain.

Participants were recruited from Med-Eng employees but only those with prior police or military training and experience were eligible. The number of participants was based on the only two standards used in this study to assess the impact attenuation that also included ergonomic requirements. BS EN 15613 [5] requires one test subject per guard size to report on mobility and comfort whereas ergonomic testing with EN 14404 [8] allows three to five subjects depending on results, i.e. if 2 out of 3 fail, two additional subjects may be used. The size of these test panels is low in comparison to the sizing study, i.e. 22 participants and a larger sample size would be preferable for aggregating feedback. Only four male volunteers from the subject pool met the service requirements and it was assumed that their opinions reflect that of the target end user, until trials with end users can be accomplished.

These four volunteers all successfully completed the obstacle course wearing one knee pad while leaving the other knee bare. This allowed the participant a direct comparison to evaluate the effect of the knee guard. The same set-up was used for the elbow guard. While on course, comments from the participants were recorded and after finishing the course, each participant completed a survey to rate their level of satisfaction on the knee and elbow guards' weight, bulk, comfort, heat build-up and persistent fit. The survey was a five-point satisfaction rating, as shown in Table 5. Scoring the knee and elbow guards separately, the participants provided a rating on weight, bulk, comfort, heat build-up and secure fit, as well as an overall rating.

Table 5: Satisfaction Rating Scale

1	2	3	4	5
Very Dissatisfied	Dissatisfied	Unsure	Satisfied	Very Satisfied

The average results of the survey responses are shown in Figure 8 for Prototype Version 1 of the knee and elbow guards (higher protection and higher weight). The volunteers used six categories to

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rate their ability to successfully complete the activities in the obstacle course. Generally, the elbow guard scored better than the knee guard. This difference, especially with respect to heat and secure fit, may be due to the trouser worn over the knee guard whereas the elbow guard was not covered. Only the weight and bulk average values exceeded the "Satisfied" rating which identified the other categories for improvement. These results, combined with the feedback which prioritized a need for better flexibility, contributed to changes implemented in Prototype Version 2.

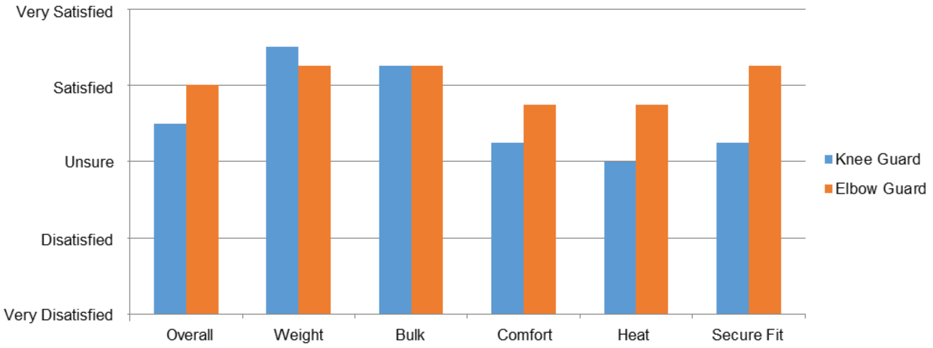

Figure 8: User Satisfaction Rating for Prototype Version 1 (higher protection/higher weight)

7. CONCLUSION AND NEXT STEPS

The project goal was achieved with the development of Prototype Version 1 of a multi-threat protection knee and elbow guard system for impact and ballistic threats. It was usable in the obstacle course and compatible with existing combat uniforms, but user satisfaction ratings were lower than expected. Based on feedback from DRDC Valcartier, the following concessions were made towards the development of a lighter-weight solution. First, protection against blunt impact could be reduced in exchange for better flexibility and mobility. The ballistic protection could also be reduced to focus on soil ejecta (IED) fragmentation instead of blast fragmentation (FSP).

A single set of Prototype Version 2 of the knee and elbow guards was then constructed in the medium size using alternate impact and ballistic materials already tested during this study. Performance indicators are displayed in Figure 9 using the best solution as the baseline. A weight rating was used as a predictor for user satisfaction because lighter weight is expected to reduce bulk and improve flexibility. These performance indicators could be prioritized and weighted accordingly to determine which version of the knee and elbow guard is the preferred solution. Additional performance indicators like comfort and ventilation, from usability trials with a greater number of participants could also be included in this determination and that will be the focus of future work.

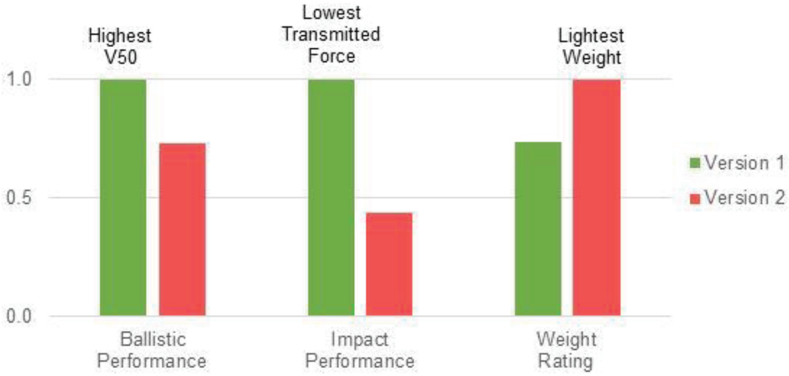

Figure 9: Performance Comparison between Prototype Versions

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