AN EVALUATION OF THE HYPODERMIC NEEDLE THREAT AGAINST BODYARMOUR

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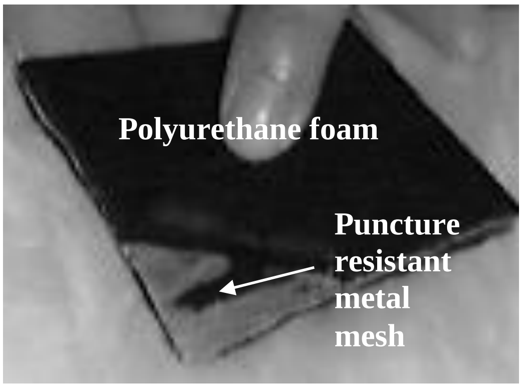
Summary
Previous work has addressed protection against stab attacks [1, 2], and slash attacks [3, 4] this has resulted in body armour that is suitable for protecting the torso against knives. Whilst this armour combats the primary lethal injuries to the torso it does not protect against minor injuries to the limbs and hands from items such as hypodermic needles and other sharp weapons. To reduce injuries to the hands from sharp weapons and needles there is a need for an effective protective glove and also a protective sleeve for the arms. This paper investigates the threats posed by hypodermic needles and examines the effectiveness of various possible needle proof systems. In order to determine the contact loads from needles that might be encountered whilst conducting body searches, male and female volunteers used an instrumented impact system to measure the average impact forces of human hand against a fixed object. The compressive loads a hand imparts as it grips an object to pick it up were also measured. A range of sizes of hypodermic needles were used to measure the puncture resistance of several lightweight armour materials and the buckling loads of the needles were also determined. This study showed that the buckling loads for hypodermic needles were much lower than typical loads measured in the human tests for accidental contact or gripping. Although a hypodermic needle is able to puncture skin easily, when puncturing armour materials the needles tended to buckle.

1. Introduction

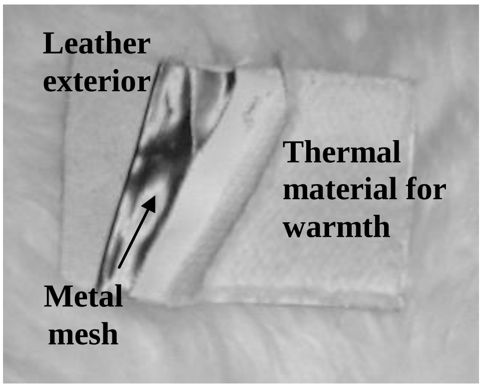
During an assault, the natural reaction of the victim is to raise his hand and forearm to deflect the attack. A wound caused by such an attack is known as the defence wound and studies have shown that the majority of these are caused by knives and other sharp instruments [5]. If the victim has grasped the sharp weapon to protect himself, the wounds will be seen on the palms of the hand and between the fingers. Katkici [5] revealed that 28 out of 51 cases of such defence wounds are on the hand.

Conflicts arise between the police and the suspect during police raids and often result in an assault on a police officer. Police Forensic Officers [6], are also required to carry out searches of crime scenes or the interior of airliners. Prison wardens are also prone to assaults and it has been reported that inmates attack prison guards once every 45 minutes in the United States [7]. Body armour provides adequate protection to the torso but to reduce any defence injuries to the hands and forearms there is a need for arm protection and gloves.

If a suspect is a drug user this is an additional hazard to police personnel particularly when conducting body searches. Contaminated syringes in the pockets of a suspect could penetrate the officers' hands during the search. Transmissions of blood borne pathogens are common amongst drug users and this exposes the police to the same degree of risk as health care workers. Needlestick injuries transmit infectious diseases, such as HIV, hepatitis B, and hepatitis C and this has prompted researches to establish why these injuries occur and to develop measures to prevent them. Needlestick and defence wounds occur mainly on the hand. When a human hand picks up objects the major risk areas are fingertips and the side of the palms. It is therefore necessary to increase the anti-syringe performance of the protective gloves in those areas. The puncture resistance of protective gloves can be increased by using several layers of different materials illustrated in figures 1(a), 1(b).



a) puncture resistant metal mesh and polyurethane foam sandwich



b) leather glove material with metal mesh acting as the puncture resistance layer

Figure 1. Typical anti syringe glove and current types of protective materials

However, this tends to make the glove cumbersome to use, figure 2. There is a still a need for puncture resistant materials that are lightweight, flexible, and wearable both for vest and glove materials.

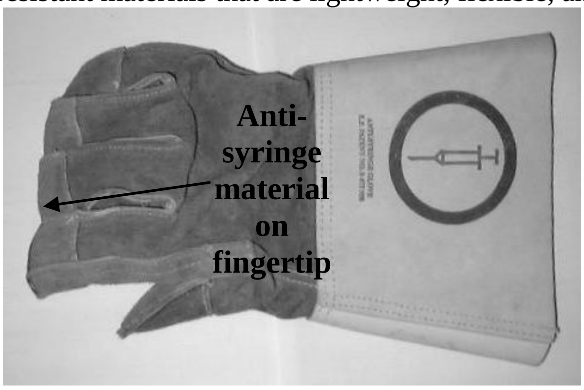


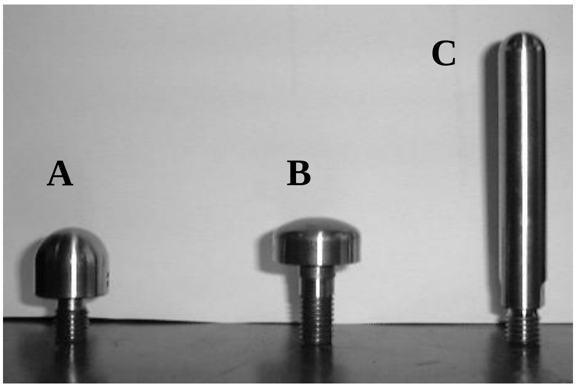
Figure 2. Typical Industrial anti-syringe leather glove

Heavy-duty anti-syringe gloves are designed to reduce the problems encountered when handling refuse that may contain hypodermic needles, broken glass and razor blades etc. The glove is not entirely needle resistant but a metal mesh layered at high-risk areas of the hand and fingertips offers high resistance to penetration [8].

If the impact and gripping forces of the hand were known, then thinner and more flexible materials resistant to these forces could be developed. The contact loads that may be encountered from needles whilst conducting body searches, were determined by male and female volunteers using an instrumented impact system to measure the average impact forces of the human hand against a fixed object. The compressive loads a hand imparts as it grips an object to pick it up were also measured. The maximum compressive force that different gauge needles can withstand without buckling and the puncture resistance of a range of protective materials was also established.

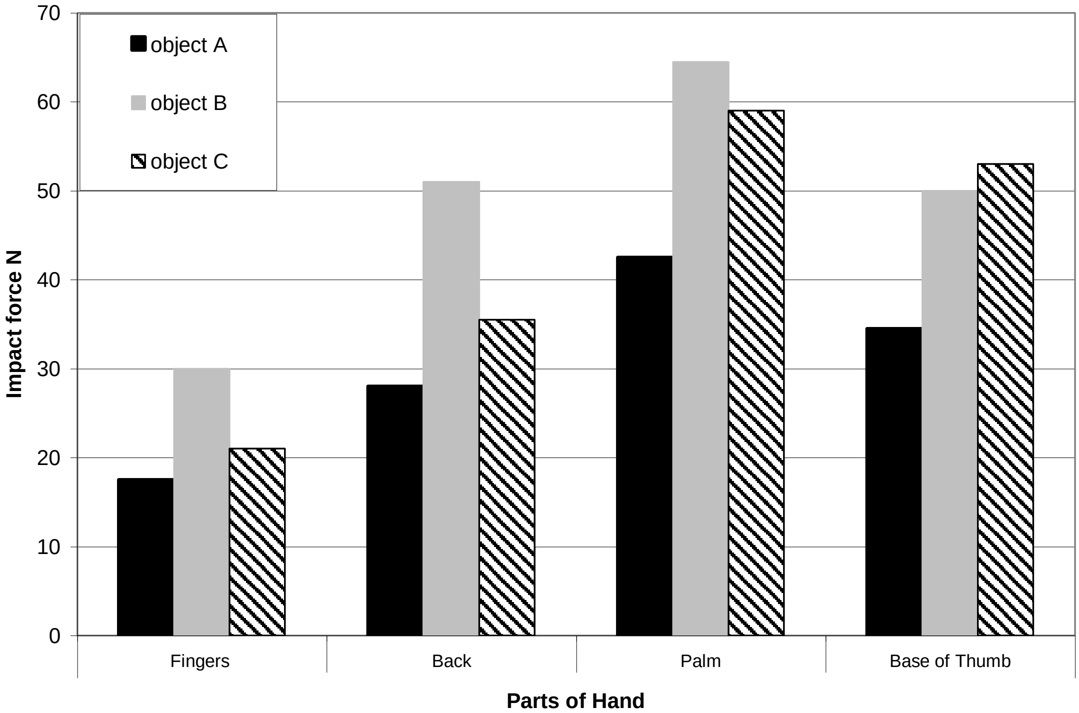
2. Contact loads

Three different sized and shaped tools to simulate objects that might be found in a pocket figure 3, were instrumented with piezo-electric pressure transducers. They were clamped in a fixed position and attached to a Rosand impact measuring system. Force and time were measured from volunteers performing 25 impacts on each of the tools using both left and right hands. Force measurements were recorded for the fingertips (F), back of hand (B), middle of palm (P) and base of the thumb (T) These data were used to obtain the average impact forces of a human hand impacting on an object, graph1.



A	15mm height 25mm radius 30mm diameter
B	10mm height 25mm curve radius 30mm diameter
C	85mm height 20mm curve radius 15mm diameter

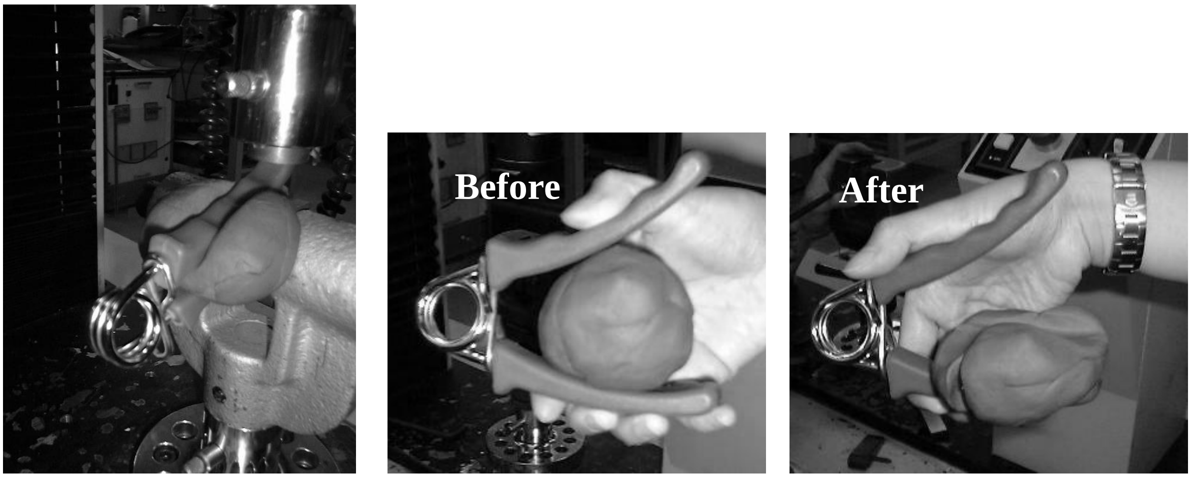
Figure 3. Tools used to determine impact forces



Graph 1: Average impact forces of different parts of a hand hitting objects A, B and C

There was some variation in contact loads between right and left hands but most significant were differences seen by which part of the hand was used and the shape of the tool. The highest loads were recorded from the flattest shaped tool (B). These results may have been influenced by the contact area available and therefore force could be applied to this shaped object more efficiently, especially from the fleshy areas of the hand. Psychological factors such as anticipated pain in striking the other shaped tools may also have influenced the test results. For all object shapes the highest loads were recorded from the palms of the hand and the lowest recorded values were from fingers. Fleshy parts of the hand allow a greater contact area with the object than fingers and therefore more force can be applied to the object.

3. Handgrip test.
A mechanical test was devised to establish the load when a human hand grips an object. A witness pack of polymer clay was inserted between the arms of a handgrip to measure the exact change in distance between the handles during compression. To determine the spring stiffness the handgrip was clamped in a fixed position in an Instron universal test machine, figure 4a. The force required to compress the clay until the arms of the handgrip met i.e. from 4cm to 0cm was then recorded.



(a) Instron compression (b) Typical result from a volunteer manually compressing the handgrip

Figure 4: Methods of measuring the maximum compressive force of a human handgrip

The spring stiffness was determined from the relationship between the maximum recorded force (N) and the maximum distance (cm) that the handgrip could be compressed. The maximum compressive force of the spring measured by the Instron load cell was found to be 150N and the change in height of the clay was 4cm, therefore the stiffness of the spring was calculated as follows:

Equation 1: $F\text{max} = kd$ where: Fmax = maximum compressive force (N)

d = change in distance (cm)

$150 = 4k \rightarrow k = 37.5$Ncm k = spring stiffness

20 volunteers were instructed to squeeze the handgrip with their writing hand once and the amount of clay compressed was measured in cm, figure 4b. Equation 1 was used to derive the maximum compressive force (F_{max}) exerted by the volunteers onto a handgrip i.e.

$F_{max} = 37.5$ x (change in distance in clay)

It was found that the average force used to compress the handgrip by men is approximately twice as much as that used by women, 130N and 71N respectively. The measured compressive force exerted on the handgrip is proposed as a model of the maximum gripping load applied when a human hand picks up an object.

4. Puncture resistance tests.

When any needle penetrates a fabric or mesh it is usually through the natural gaps caused by the weave. If the needle hits an individual fibre or wire the contact stress applied by the needle tip must be greater than the resistive stress of the material. As stress is calculated from force per unit area large contact stresses will be concentrated at the tip of fine needles. If these stresses are high enough to allow a needle to puncture a hole in a material the profile of the needle will allow the needle to slide through and penetrate. An ideal needle resistant material will defeat the puncture mechanism by causing the needle to buckle or if puncture occurs, causing friction on the sides of the needle impeding the path of needle as it penetrates.

An Instron 4206 universal testing machine in compression mode was used to determine the puncture resistance of several lightweight protective materials:

a. Lightweight 304 Hollander woven wine cloth metal mesh with wire diameter 0.068mm (transverse) x 0.040mm (longitudinal).
b. Heavyweight 304 Hollander woven metal mesh with wire diameter 0.125mm (transverse) x 0.090mm (longitudinal).
c. 200g/m^2 woven Kevlar 129 coated with 4 layers polyurethane varnish. Prepared in the laboratory the first two coats were left to dry for 2-3hrs to allow the varnish to saturate the material. A further two layers were applied and the material was left to dry for 3 days.
d. A commercially available knife resistant polymer film coated aramid
e. 200g/m^2 woven Kevlar 129 coated with araldite® (20ml of hardener/40ml of resin) prepared in the laboratory and left to dry for 24 hours.
f. Polythene coated aramid manufactured for RMCS by Permali UK Ltd.

Four needle gauge sizes were used: 25G, 23G, 21G and 19G, the larger the gauge number the smaller the diameter. A standard PSDB stab resistance foam test block [1] was used as a backing material for all the fabrics tested. A new needle attached to a syringe was used for each test, then fitted into the Instron machine the force required to puncture the specimen was measured. If the needle did not puncture the specimen, the force required to buckle the needle was measured. 10 tests were carried out with each gauge of needle on each specimen type, the results of the maximum recorded forces were averaged and are shown in table1.

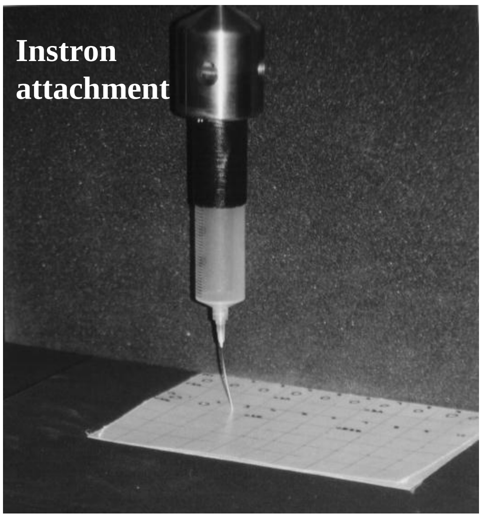


Figure 5. Test set-up showing machine, position of specimen and foam backing

Hollander woven wine cloth metal mesh

A single layer of Hollander lightweight metal mesh (a) did not provide any puncture resistance against hypodermic needles. All needles were able to penetrate the test material easily with a compressive force of only <10N. Two layers of the lightweight metal mesh and the heavyweight metal mesh (b) were resistant against hypodermic needle penetrations and caused the needles to fail by buckling. The average maximum buckling load a 25-gauge needle could withstand, when trying to penetrate a two layers of lightweight metal mesh was 10N and 6N on heavyweight metal mesh, table 1. The heavyweight metal mesh prevented puncture primarily because its wire diameter was larger than that of the needle tips. However, when compared with the lightweight metal mesh, the larger wire diameter will have larger spaces between the weave. This increases the risk of the needle tips penetrating these spaces by forcing the wire apart. The second layer of the lightweight metal mesh doubled the stiffness and increased resistance to the puncture process. The diameter of the wire provided more cross-over points, if these were not aligned exactly with the wire in the first layer the resistance to perforation is increased similar to the effect illustrated in figure 7.

Table 1. Average maximum load a needle exerted on metal meshes and coated aramids

Material type	**Number of layers**	**Needle failure mechanisim Perforation/ buckling**	**Average Max Load (N)**			
			25G	**23G**	**21G**	**19G**
Hollander cloth - metal mesh						
Lightweight	single layer	all needles perforated	10	6	9	7
	2 layers	buckling	10	11	20	24
Heavyweight	single layer	buckling	6	6	5	8
Coated Aramids						
Polyurethane	5 layers	all needles perforated	2	7	3	2
Commercial polymer coated aramid	1 layer	all needles perforated	5	6	8	9
	3 layers	all needles perforated	9	11	14	16
	5 layers	buckling	8	13	15	25
Araldite® coated	3 layers	all needles perforated	10	10	12	12
	5 layers	buckling	13	12	16	22
Polythene coated aramid	4 layers	buckling	18	16	19	23

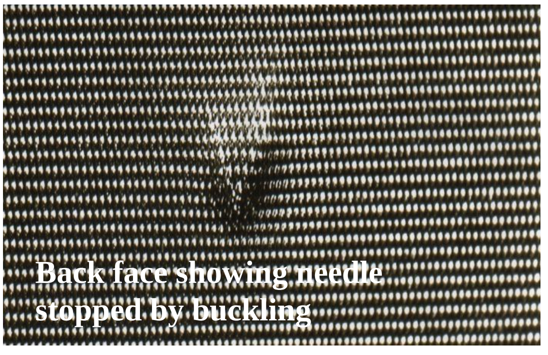


Figure 6. Puncture damage to lightweight metal mesh viewed under the microscope (x20)

The polyurethane coated aramid prepared in the laboratory did not provide any penetration resistance against hypodermic needles. The polyurethane penetrated the weave and coated the aramid fibres well. However, it did not fill the holes in between the weave and the needles could enlarge these spaces and pass through the fabric easily.

Five layers of commercially coated knife resistant aramid were required to resist most punctures by syringe needles. Only 5% of the tips of the needles tested penetrated all 5 layers and the five layers caused buckling at the needle tips, figure 7.

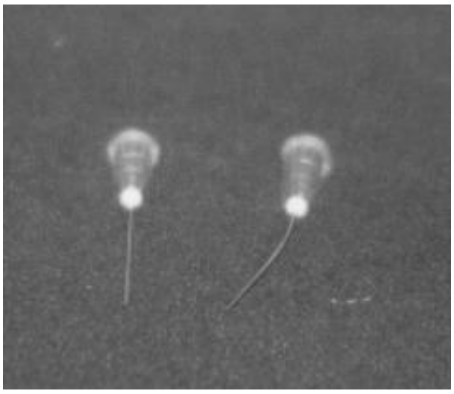
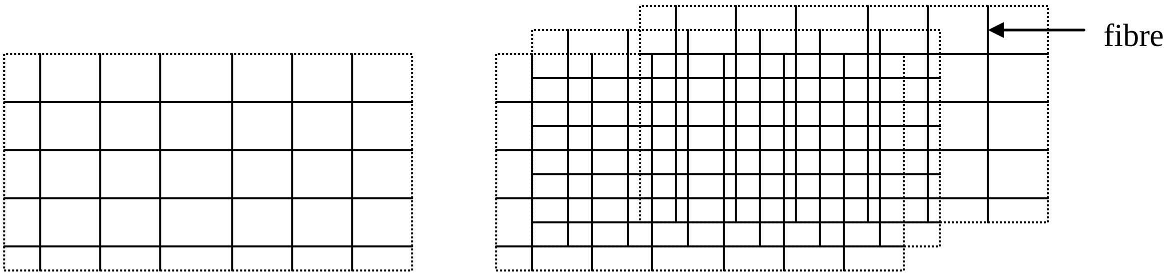


Figure 7. Buckling failure in hypodermic needles

84% of the needles tested were stopped at or before 2 layers, 12% by the third layer and 4% by the fourth layer. The fibres of the different layers were out of phase making it difficult for the needle to find and penetrate the holes in between the weaves at exactly the same position, as shown in figure 8.



(a) Layers of woven aramid with fibres aligned, needle can easily penetrate through gaps

(b) Layers of woven aramid with fibres not aligned,(out of phase) reducing gaps therefore more difficult for needle to penetrate

Figure 8. Effect of fibre alignment

Five layers of Araldite® coated Kevlar successfully stopped needle penetration with most needles stopped by the third layer. Coating the surface of aramid with the epoxy resin improved the puncture resistance as the coating acted as an extra layer of material. However, Araldite® reduced the flexibility and increased the thickness of the fabric as it did not permeate the aramid fibres. To avoid this the Araldite® should be of a viscosity to allow it permeate through the fabric, so that the spaces between the weaves are blocked reducing the risk of needle penetration, figure 9.

(a) needle penetrated unplugged hole in Kevlar

(b) needle buckled by araldite filled hole (shaded in black)

Figure 9. (a) Non-treated and (b) treated Kevlar

All needles penetrated three layers of the polythene coated Kevlar supplied by Permali Gloucester UK. Four layers were required to prevent perforation by all needles with most being stopped by the second layer. The extra layer provides extra stiffness and this may enhance puncture resistance. Also the manufacturing process allowed the polythene molecules to permeate the Kevlar® plugging the holes between the weaves and therefore making it difficult for the needle to move fibres apart to make a hole figure 9. This fabric resisted approximately 23N of compressive force with a 19-gauge needle. This was comparable to the resistive force of the Araldite® coated aramid. However, laboratory produced Araldite® coated Kevlar was twice as thick and not as flexible as those manufactured by Permali.

Conclusions

The buckling load for a hypodermic needle on the materials tested was found to be approximately 25N. Buckling failure is an effective mechanism in defeating a needle as its causes the needle to bend and flatten. Approximately five layers of coated aramid resisted perforation until the load was great enough to cause the needle to needle buckle. Layers of tightly woven aramid have better puncture resistance as the fibres are less able to move and allow the needle to pass through. Applying coatings to these aramids enhances their puncture resistance as the coating blocks any small spaces in the weave preventing sideways movement and impeding the passage of the needle.

The average impact force when a human hand impacts on an object was approximately 20N for fingers and 65N for the middle of the palm. The average compressive force when a human hand picks up an object was approximately 130N for males and 71N for females. Protective gloves should aim to resist these forces to offer protection against accidental puncture wounds caused by gripping or encountering sharp weapons during search procedures.

There is a need for wearable arm protectors and gloves to reduce defence injuries to the hands and forearms. Some current ballistic and stab resistant body armour systems may have up to 35 layers of coated aramid included in their construction. This work has shown that adequate protection from needle attacks against the vunerable areas of the hands and forearms could be achieved with fewer layers of this fabric resulting in increased wearability of protective equipment.

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