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PAPER

ENGINEERING SCIENCES; PATHOLOGY/BIOLOGY

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Forces Required for a Knife to Penetrate a Variety of Clothing Types

ABSTRACT: In stabbing incidents, it is usual for the victim to be clothed and therefore a knife penetrates both clothes and skin. Clothes (other than leather) have been thought to make little difference to the penetration force. However, there is little quantitative data in the literature. In this study, a range of clothes have been tested, either singly or in layers of, for example, T-shirt and shirt, to quantify the additional force required when clothes are present. A materials testing system has been used to test the penetration force required to stab through clothes into a foam–silicone rubber skin simulant. The results show that the force required can be significantly different, particularly when layers of clothing are penetrated. A cotton t-shirt adds *c.* 8 N to the penetration force, while a T-shirt and jacket can add an additional 21 N. The results allow a more quantitative assessment of forces required in stabbing.

KEYWORDS: forensic science, knife, force, stabbing, clothing

Stabbing is the most common method of committing homicide in the United Kingdom. Weapons that are frequently used in such attacks include kitchen knives, utility knives, sheath knives, penknives, scissors, samurai swords, bayonets, screwdrivers, and glass bottles (1,2). Following such incidents, the forensic pathologist is often requested to estimate the degree of force involved (1,3). One factor to be taken into account is how much of an influence the victim's clothing had on the resistance met to the penetration of the weapon. Some authors have made general observations that clothing can cause differences in the amount of effort [force] required to penetrate skin (4), and although a study by Kemp et al. (5) did contain force data for generic drill and knit fabrics, to the authors knowledge, there is no published quantitative data for how different clothing/fabric types influence the penetration force required for stabbing.

To date, the principal area of research into the force required for a weapon/projectile to penetrate clothing has been conducted in the field of protective clothing. This work has been focused on trying to prevent penetration and minimize the severity of injuries. Through this work, fabrics that can be used for protective garments have been considered in detail including their compositions, construction, weave, and also the combinations of these fabrics and the ordering of layering them (6–8). Clearly, the additional force for penetration of protective clothing such as stab vests is considerable. For example, a slash vest consisting of Kevlar and Jersey can require up to 234.4 N to penetrate (6).

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Despite this work, to our knowledge, no quantitative data have been published investigating the force required for penetration of normal everyday clothing. The aim of the work in this study was to quantify the varying additional amounts of force required for three types of knives to penetrate a variety of nonprotective clothing types and to consider the effect of layering of clothes on penetration. The effect of fabric weave type, number of layers, and knife tip characteristics are considered. This data will allow forensic practitioners to make a more quantitative assessment of the significance of clothing on altering the force required for penetration of a knife into the body. This will allow for a more scientific analysis in providing an estimation of the amount of force involved in a stabbing where a victim is wearing clothes.

Materials and Methods

The experimental protocol and skin simulant listed were similar to that previously published in a study considering the force required for broken glass bottles to penetrate skin (2). A skin simulant was chosen as it is difficult to use human skin within the United Kingdom owing to ethical difficulties and also because it gives highly reproducible results compared with that of animal skin. For the purposes of this study, a skin simulant was more appropriate than using animal skin due to the inherent variability of skin between individuals and within varying areas of an individual's body.

The skin simulant comprised of a combination of foam and silicone rubber, which gives reproducible results that are comparable with those of human skin (1,2,9–16). This combination provides a realistic elastic deformation response during penetration, that is, deflecting in a manner similar to that of skin. An open-cell polyether foam with a foam hardness in the region of 125–155 N and a density of 23–28 kg/m^2 was chosen for this study (Acoustafoam, Shropshire, England). This was covered by a layer of silicone rubber (2,10). The silicone rubber used consisted of two parts mixed in a 1:10 ratio. A total of 150 g of the base (part B, transil 40) was mixed with 15 g of catalyst/curing agent (part A, transil 55) for between 3 and 5 min (Mouldlife, Newmarket, England) (2). The mixture was then poured into a specially designed mold and spread out evenly to make a thin uniform layer (2). A piece of polyether foam was then placed on top of the mold before the final set to create a good bond between the skin and foam and left to set for 24 h (2).

Three different cooks' knives with similar profiles were used in this study (Table 1). The only selection criteria for the knives were that they should be readily available and reasonably priced in an effort to make them representative of kitchen knives used in stabbings. A variety of clothing was used, which was collected in the form of donations from colleagues (Table 2). This allowed a representative sample of current clothing as could be worn within the community to be examined. Each piece of clothing was tested individually with the skin simulant and when layered on top of a 100% cotton T-shirt (T-shirt 1), which was placed over the skin simulant (Table 2). Each knife was used three times on each set of clothing, and an average was taken. For each test, the blade remained in a fixed position, perpendicular to the skin simulant/clothing. Although the blade remained in the same position, the clothing was simply positioned underneath the blade in no particular orientation. A control group of tests were carried out in which each knife penetrated the skin simulant three times without clothing.

Load and displacement of the knife into the skin simulant were continuously measured using a Material Testing System (MTS) (Hounsfield Test Equipment Ltd, Surrey, U.K.) (2,15).

TABLE 1—*Description of knives tested.*

Manufacturer	Kitchen Devil (KD)	Stellar 1 (S1)	Stellar James Martin (SJM)
Condition	New	New	New
Knife type	Cooks' knife	Cooks' knife	Cooks' knife
Blade thickness (mm)	0.11	0.14	0.16
Tip angle (Plan)	64.8°	103.5°	74.1°
Tip radius (Rp) (mm) (Plan)	0.0631	Triangular tip	Triangular tip
Edge radius (Rt) (mm)	Triangular	Triangular	Triangular
Weight of knife (g)	100	160	138

Plan, tip angle; Rp, tip radius; Rt, edge radius.

TABLE 2—*Description of garments tested.*

Type of Clothing	Type of Material
T-shirt 1	100% cotton
T-shirt 2	100% cotton
T-shirt 3	100% polyester
Shirt 1	65% cotton, 35% polyester
Shirt 2	65% cotton, 35% polyester
Shirt 3	100% cotton
Rugby top	100% cotton
Sweatshirt	50% cotton, 50% polyester
Jacket 1	100% polyester
Jacket 2	100% polyester
Jacket 3	100% leather, 100% polyester lining
Fur coat	Unknown
Slash hoodie	Outer/inner linings unknown and middle layer constructed of aramid fiber
Jeans 1	100% cotton
Jeans 2	98% cotton, 2% elastin

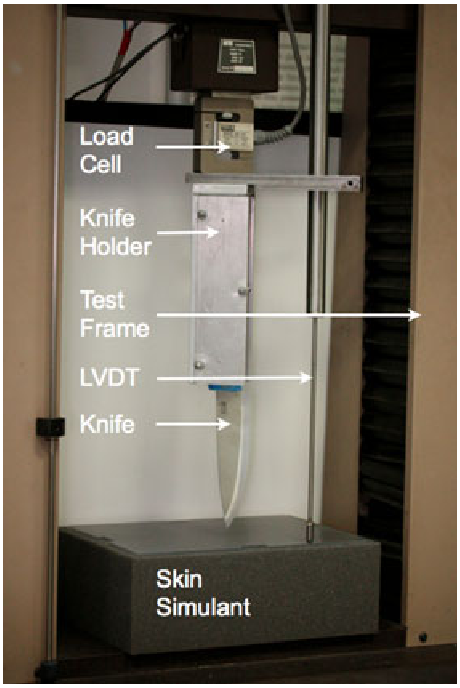

FIG. 1—*Detailed view of the materials testing system.*

The experimental setup can be seen in Fig. 1. The MTS can be used in either tension, to pull materials to failure, or in compression to test materials response to compression/indentation (2). In the system, a moving crosshead is used to push or pull the material under test, combined with a load cell, which is used to determine the magnitude of the applied load (2). The displacement is obtained from either monitoring the crosshead speed and inferring displacement or more accurately by using a linear variable displacement transformer (LVDT) giving an independent measurement of displacement (2). For each knife and set of clothing, the force required to push the knife into the skin simulant and the displacement of the knife into the skin simulant was recorded simultaneously, using the MTS and LVDT. From this data, load versus displacement plots were produced (Fig. 2).

Results

Load–displacement curves show a characteristic step that correlates with skin penetration (Fig. 2). Thus, the maximum force for penetration can be determined for each knife for each experiment. The average force required for penetrating the skin simulant alone, that is, without clothing for the three different knives, was 10.97 N for the Kitchen Devil (KD) knife, 9.95 N for the Stellar 1 (S1) knife, and 9.67 N for the Stellar James Martin (SJM) knife, respectively. This gave a baseline against which the results for testing with clothes were compared.

When testing with clothes, the step in the load–displacement curve was found to be less pronounced compared with when no clothing was present. On some occasions, the load–displacement curves contained more than one peak, although this did not necessarily correspond to the number of layers of clothing. In such instances, the most characteristic peak was used as the minimum force for penetration (Fig. 3). The average penetration forces indicated that, although there was a general trend in the force required for penetration, this varied with each item of clothing for each knife (Fig. 4).

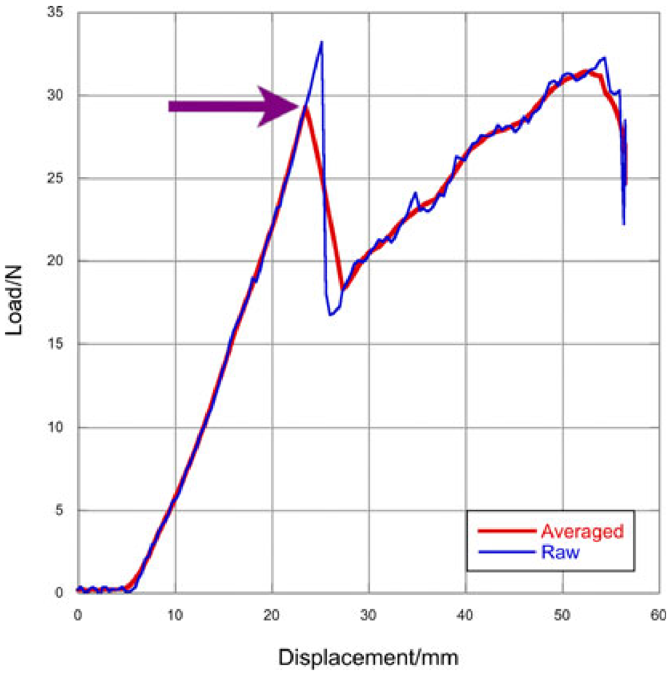

FIG. 2—*Load–displacement curve demonstrating characteristic step at the point of penetration (arrow).*

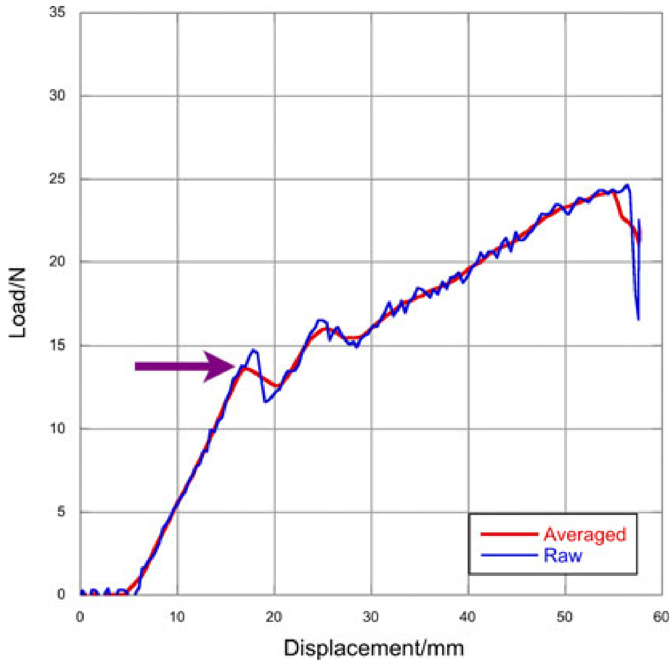

FIG. 3—*Load–displacement curve showing several peaks, and the point of penetration is indicated by the arrow.*

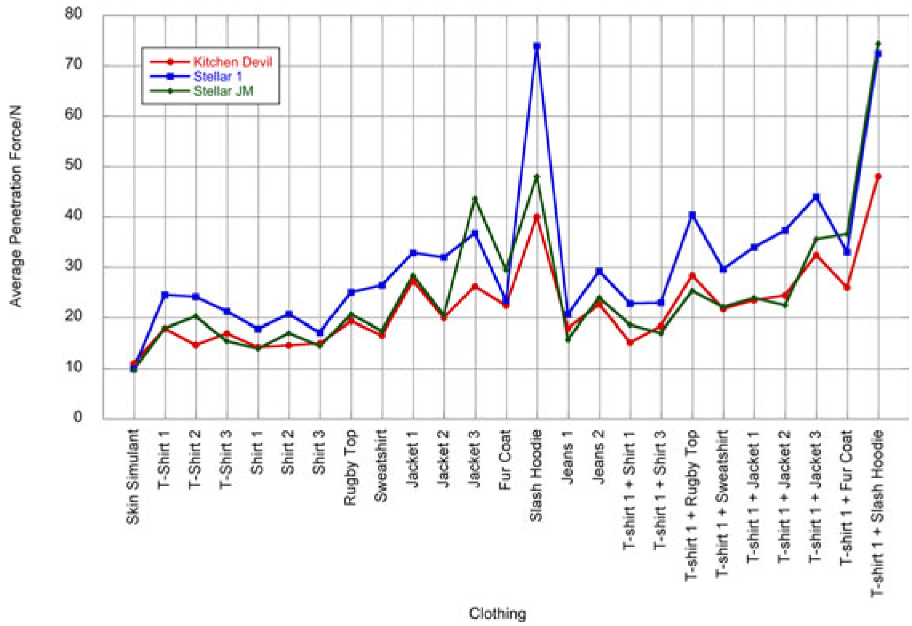

FIG. 4—*The average penetration force for each item of clothing/combination.*

The layering of fabrics resulted in a greater cumulative force required for penetration than that for the single item in the layering for the majority of experiments. However, in one case, the KD knife measured an average penetration force of 17.83 and 27.19 N for the T-shirt 1 and Jacket 1 (see Table 2 and Fig. 4), respectively, but measured 23.39 N in combination. This unexpected result may be as a result of the construction of the garment. Jacket 1 is 100% polyester and consists of an outer layer and inner mesh lining with the only one fixing point at the zip. As a result, the inner and outer layers can move freely, sliding over one another. When the jacket is layered with T-shirt 1, it could possibly create friction between the mesh lining and the t-shirt, effectively anchoring the garment and allowing the knife to penetrate more easily.

The effect of orientation of the blade to the alignment of the fabric weave on the force required for penetration was also examined. For the tests conducted on Jeans 1 (see Table 2) with the S1 knife, the forces required for penetration were 18.66, 21.87, and 21.20 N for three different stabs (see Fig. 4). All the stabs diagonally transect the weft and warp (Fig. 5) in similar

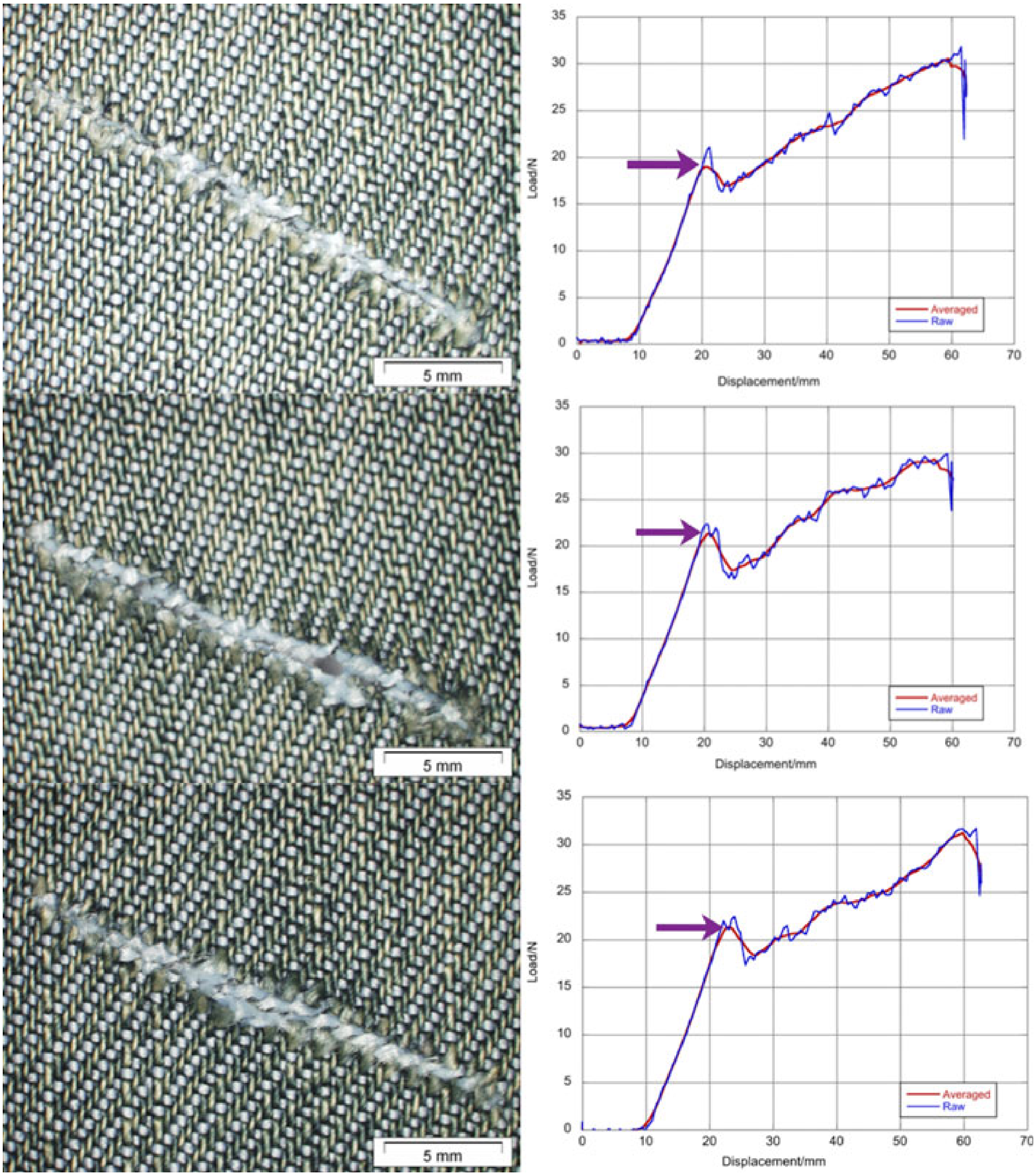

FIG. 5—*Images and load–displacement graphs for three stabs into Jeans 1 using Stellar 1 knife. The arrow indicates point of penetration.*

orientations. Thus, there is a range of *c*. 3 N for the different stabs. For tests on Shirt 1 (see Table 2), the penetration forces were 17.69 and 18.80 N (see Fig. 4), respectively, for two stabs approximately in line with the weft of the fabric (see Fig. 6). A further stab that diagonally transected the weft and warp (see Fig. 6) gave a penetration force of 14.71 N (see Fig. 4). Consequently, the orientation of the knife in relation to the weave does appear to have a small effect on the penetration force. Jeans 1 and Shirt 1 had different weaves of the fabrics (e.g., density of fibers), and thus, this accounts for the small difference in overall force for penetration required between the two. The results show that different weaves of fabric can account for variations in force. In this case, Jeans 1 has a larger yarn thickness and smaller thread density, in comparison with Shirt 1, which has a smaller yarn thickness and larger thread density. With Jeans 1 requiring greater force to penetrate than Shirt 1, it seems reasonable to suggest that it is the yarn thickness that is of greatest importance, with regard to the fabric, when considering penetration force.

This study is aimed at providing quantitative data for the force required for penetration of normal day-to-day clothes as worn by community. However, with U.K. knife crime ever increasing, and the threat it poses, many people have begun to purchase antislash garments. These garments are designed as "fashionable" items such as hoodies and are particularly prevalent in areas of perceived high crime rates such as London and Glasgow. This method of covert protection appeals to many people as it is not obvious to potential attackers and is much more affordable than other protective clothing such as stab vests. Thus, as part of this study, a new "slash hoodie" (white covert hooded top lined with

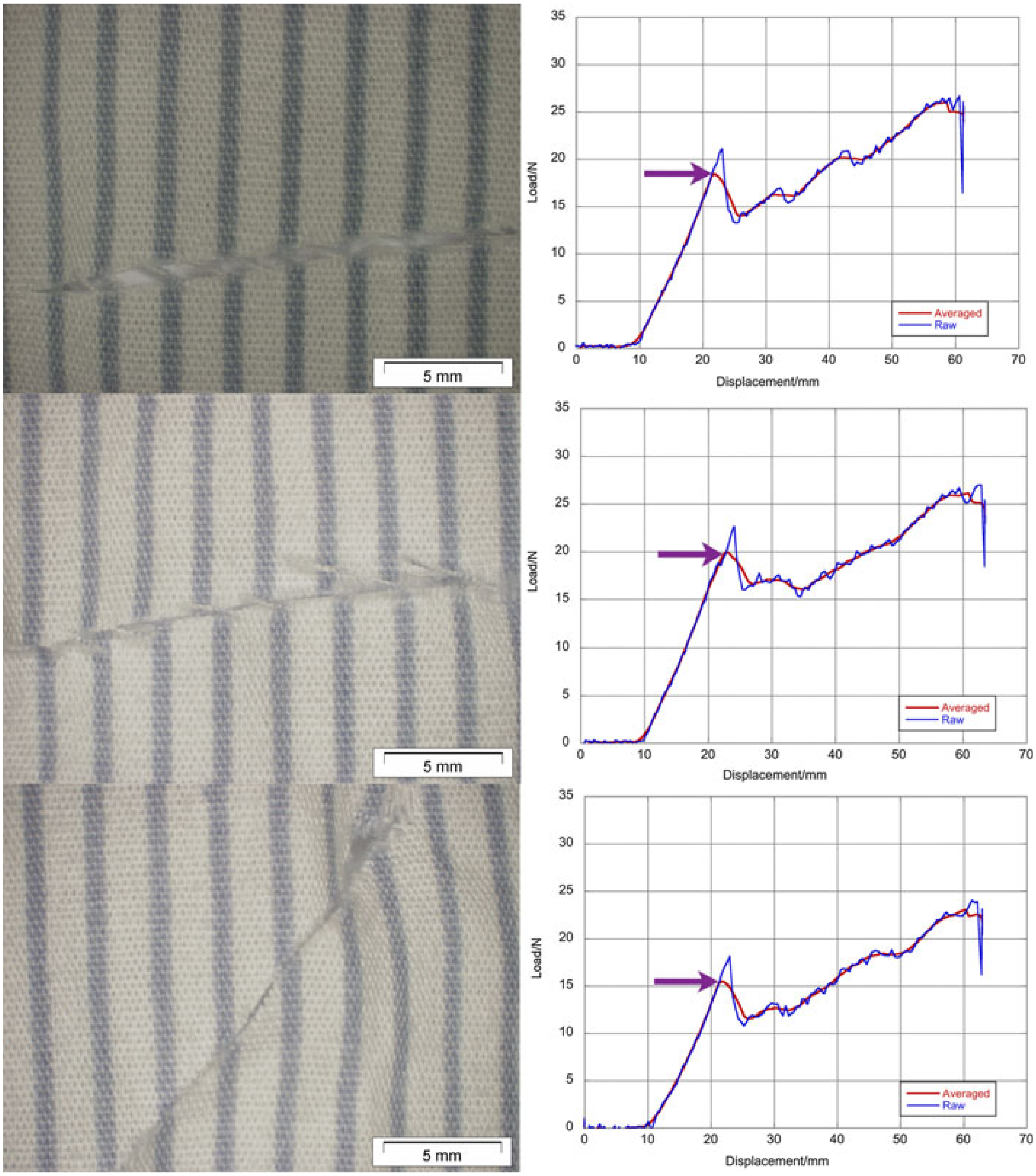

FIG. 6—*Images and load–displacement graphs for three stabs into Shirt 1 using Stellar 1 knife. The arrow indicates point of penetration.*

aramid fiber) was purchased from www.bladerunner.tv. The information on the companies website states that this garment is "tested in accordance with EN388, 6.2—Blade cut resistance, and has achieved level 2." BS EN 388:2003 is a measure of how many cycles it takes for a rotating circular blade to cut through a material under specific conditions and is specific for gloves (6). A more appropriate test for this type of garment would have been the BS EN ISO 13997:1997, which details a test to determine a fabrics' resistance to cutting using sharp objects, and was designed for all types of protective garments (6).

The hoodie is only said to provide "antislash protection," but as most knife attacks often contain a combination of both stabs and slashes, it seemed appropriate to test this item as well. In the tests, the slash hoodie required the most force for penetration for each knife, even reaching 74.35 N when combined with T-shirt 1 (Fig. 7). This is *c*. 60 N greater than for the skin simulant alone. Aramid fibers are commonly used in jackets for providing ballistic protection (6,7). It is known that the strength of the aramid fibers degrades over time, and thus, it should be emphasized that our tests were carried out on a new hoodie. The hoodie contained multiple layers, an outer layer of fabric underneath which is a layer of aramid fiber followed by an inner mesh. (Note that the results should not be used to infer that the garment provides any stab protection.)

Discussion

Fabric damage examination is a routine task for the forensic scientist in an attempt to provide more information on possible cause of death (5). Current forensic work involving clothing and

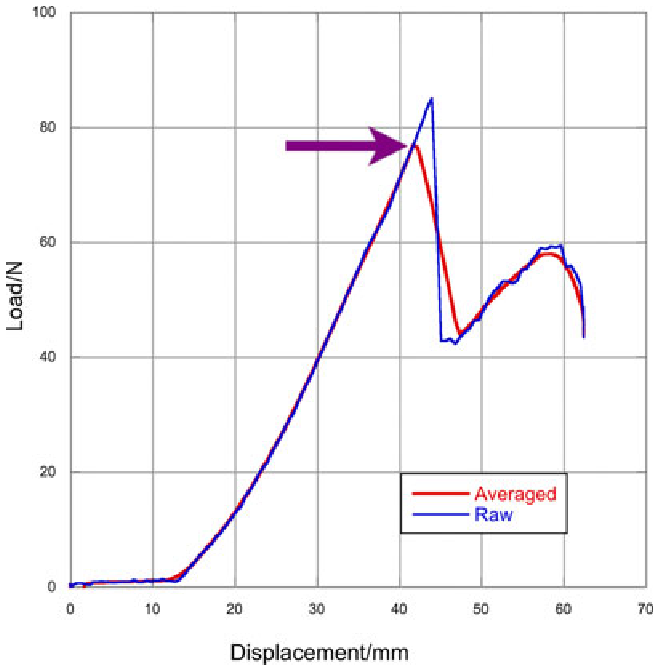

FIG. 7—*Load–displacement curve for slash hoodie, and the point of penetration is indicated by the arrow.*

knives has been aimed at taking evidence left in clothing by a knife, such as trace evidence or by examining the fabric to gain estimates of the knives' geometry and possible angle of attack. Some work has also been carried out to try and find a correlation between wound and size and fabric damage (17). In most instances of stabbing, the area of the body is covered by at least one item of clothing. Ambade and Godbole (18) found that the thorax was the most frequent location of sharp force stabbing incidents (72.5%) followed by the abdomen (42.9%), and thus, it is important to better understand the role that clothing plays in changing the force required for penetration.

Recent research by Daroux et al. (19) has shown the importance of the number of times an item of clothing has been laundered with regard to its value as forensic evidence. This is particularly important when garments are examined for fabric distortion or disorder, and fiber end morphology as a means of estimating weapon morphology or angle of attack (5,19). However, as the item(s) of clothing are usually available for examination, and most people are unaware of the number of times an item of clothing has been washed (unless brand new), the number of times the item has been laundered may influence the damage seen on the fibers but does not help in terms of determining the force required to stab through a particular garment.

Previously, the effect of clothing has been considered to have minimal effect on the degree of force required for stabbing with sharp weapons, although there was, to our knowledge, no previously published quantitative data to substantiate this conclusion. The results of this study show that clothing does have an impact on the amount of force required for penetration, adding to the amount of force required to achieve penetration. This increase in force is variable and does not appear to have a correlation between the type of fabric and blade. Simply adding a T-shirt or cotton shirt

FIG. 8—*Composite image showing the three knives used in this study and their tip angles. Kitchen Devil (top) 64.8°, Stellar 1 (middle) 103.5°, and Stellar James Martin (bottom) 74.1°.*

typically added around 5–10 N for the knife to penetrate through a shirt–skin simulant system. From the sample of clothing tested, it was the "slash hoodie" that required the greatest amount of force for penetration, adding between 29.01 and 63.97 N. The most likely explanation for this is the presence of a layer of aramid fibers, which are well known for their strength. For the majority of cases, multiple layers require more force than single layers, although this relationship appears to be more complex than a simple additive relationship.

Some variability in the force required to penetrate with different weapons was seen for the three different knives tested. This variability is not directly linked to any feature of the knife and suggests that it is the clothing type that has the greatest effect on penetration force rather than the features of the knife. This is interesting as in the previous work, it was the tip radius that had the greatest influence on penetration force. In this study, two of the knives had triangular tips. Thus, it was inappropriate to use tip radius and so tip angle was considered. The results of this study show that tip angle accounts for the variability seen between the knives (Fig. 8 and Table 1). Both knives KD and SJM have similar tip angles (64.8° and 74.1°, respectively) and have the least variability and closest pattern of penetration forces (see Fig. 4), whereas knife S1 has a much larger tip angle (103.5°) and has the most variability in penetration forces (see Fig. 4). Although tip angle was considered instead of tip radius, it reaffirms that it is the tip characteristics that are most important when considering penetration force.

The mechanism of knife penetration through clothing starts with the tip initially penetrating the fabric weave and then the edge of the blade cutting through the various fibers. The most important factors controlling how much additional force is required for penetration with clothing therefore depends on the density of the weave and the strength of the yarn used in the clothing. This accounts for the fact that cotton T-shirts, shirts, and jeans all require the addition of broadly similar amounts of force as the cotton yarn will have similar strengths. Considering that the orientation of the knife to the weave affects the magnitude of the additional force required for penetration reinforces the significance of these factors. Therefore, it is recommended that for forensic purposes, tests to determine how much additional force is required for penetration of garments should be made in the same orientation as any knife marks on the fabric.

This study has provided the first set of quantitative data for the force required for penetration of knives for a variety of clothing. It is important to note that the results of this study are aimed at highlighting the importance of considering clothing in cases of penetration. For casework, the specific clothing present in the case must be tested rather than inferring force data from that provided in this study, and other considerations such as knife velocity, knife angle, and the fact that the underlying skin may have an influence should be taken into account. Further work on studying cadaveric or animal tissue may be beneficial to see whether the results here are reproduced under a greater range of test conditions, although the fact that the properties of human and animal skin vary may add further complexity.

Conclusion

In summary, we have considered the effect of clothing on the forces required for penetration with sharp weapons. This was achieved by conducting a series of penetration tests using an MTS in combination with an LVDT, a skin simulant, three cooks' knives, and a variety of garments. The findings are outlined:

- From the results obtained, we have shown that clothing affects the amount of force required to penetrate a skin simulant with a sharp weapon. The additional force can be significant particularly if multiple layers of clothing are involved.
- Multiple layers of fabric generally require more force to penetrate than single layers, although there is no simple additive relationship between the force for penetration of multiple layers and the force required for single layers.
- The addition of a T-shirt or cotton shirt typically added around 5–10 N for the knife to penetrate through a shirt–skin simulant system.
- Of the clothing tested, the "slash hoodie" caused the greatest increase in force required for penetration.
- Previously, it was thought that leather would have the greatest influence on force, and the results here also support this observation for the standard clothing tested.
- Some variability in the force required to penetrate with different weapons was seen. The knife with the biggest tip angle demonstrated the largest variability and also required the most force to penetrate the clothes.
- The mechanism of knife penetration is by the tip initially penetrating the fabric weave and then the edge of the blade cutting through the various fibers.
- The important factors controlling how much additional force is required for penetration with clothing are the density of the weave, the thickness, and strength of the yarn used in the clothing.
- Cotton T-shirts, shirts, and jeans all require the addition of broadly similar amounts of force as the cotton yarn will have similar strengths.
- Finally, the orientation of the knife to the weave affects the magnitude of the additional force required for penetration, and therefore for forensic purposes, tests to determine how much additional force is required for particular garments should be made in the same orientation as any knife marks on the fabric.

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