



A combined experimental and numerical study of stab-penetration forces



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ABSTRACT

The magnitude of force used in a stabbing incident can be difficult to quantify, although the estimate given by forensic pathologists is often seen as 'critical' evidence in medico-legal situations. The main objective of this study is to develop a quantitative measure of the force associated with a knife stabbing biological tissue, using a combined experimental and numerical technique. A series of stab-penetration tests were performed to quantify the force required for a blade to penetrate skin at various speeds and using different 'sharp' instruments. A computational model of blade penetration was developed using ABAQUS/EXPLICIT, a non-linear finite element analysis (FEA) commercial package. This model, which incorporated element deletion along with a suitable failure criterion, is capable of systematically quantifying the effect of the many variables affecting a stab event. This quantitative data could, in time, lead to the development of a predictive model that could help indicate the level of force used in a particular stabbing incident.

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1. Introduction

When a stabbing is fatal, the amount of force required to inflict the stab wound is often the source of much debate in court. It is, of course, in the interest of the prosecution to claim that the level of force was severe or frenzied, and conversely the defense would rather have the force described as mild or benign. It is inevitable that the forensic pathologist, as an expert witness, will be asked to quantify the force involved in the stabbing attack. It is impossible to exactly quantify the force exerted, although a qualitative assessment can be made by the pathologist, based on the condition of the blade, the tissue type damaged, the depth of the wound and the clothing present [1].

Based on this assessment the answer given by the expert witness will be a qualitative description using comparative adjectives such as 'mild', 'moderate', 'considerable' or 'severe'. The problem with such descriptions is that their interpretation is highly subjective. For example, an expert witness might consider a

particular force to be moderate and a juror may consider the same force to be severe.

While the problem described here is unique to forensic pathology, it is clear that it could benefit from an interdisciplinary approach incorporating biomechanics. In recent years, the fields of biomechanics and forensic medicine have merged to form a new discipline, forensic biomechanics. This discipline has met the needs of the legal system in particular, with biomechanists increasingly acting as expert witnesses in a court of law [2]. Previous studies on the topic of stab penetration have focused on experimental testing alone [3–8]. In this study, data obtained through experimentation has been used to develop a finite element model of stab penetration. Finite element analysis (FEA), first used in the 1950s as a tool for aeronautical engineering, has become an invaluable tool in biomechanics over the last three decades [9]. The model developed here replicates the conditions of a laboratory stab-penetration test and uses the Von Mises stress criterion coupled with element deletion to model the failure of the skin. The chief advantage of developing such a model is that once the development process is complete, the model can be used to investigate the influence of the many parameters associated with stabbing incidents. While this model is a simplified version of a real life stabbing event, it is nonetheless the first fully developed FEA model which simulates the penetration of a blade into human skin. In time, such models

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could potentially be used to estimate the level of force used in stabbing incidents.

2. Materials and methods

2.1. Experimental

Stab-penetration tests were performed on porcine skin and polyurethane and a limited number of tests were performed on human skin. Tests involving human skin were carried out in IFSTTAR, Lyon, France. French law allows human corpses that have been donated to science to be used for research purposes. The ethics committee within IFSTTAR approved the use of human biological material. The porcine skin was sourced from 22 week old female farmed pigs and was obtained directly from a local abattoir. Human skin was excised from the back and porcine skin was excised from either the back or the belly. The thickness of human skin after removal of adipose tissue was measured using a Vernier calipers and the mean thickness was 2.6 mm. The mean thickness of the porcine skin and polyurethane was 2.3 mm and 2 mm respectively.

The skin was cut into a cruciform shape using a custom made die. Open-cell polyethylene foam of density 35 kg/m³ was placed below the target material to ensure that it did not deform nor vibrate excessively, which would not be representative of a real-life scenario. Open-cell polyethylene foam has previously been found to be a suitable surrogate material [10,11,8] and this density is close to that used by [10] and by [11].

Experiments were carried out at a range of test speeds from 100 mm/min (quasi-static) to 9.2 m/s, consistent with the typical maximum velocity of the arm in a stabbing motion [12,10]. The experimental set-up for the stab-penetration tests requires three main devices: The biaxial tension device, whose primary function is to hold the test material in place, the blade holder, whose function is to secure the blade or other implement in place on the test machine, and the test machine itself. We used a Tinius Olsen universal testing machine for the quasi-static tests and a Rosand droptower for the dynamic tests. The biaxial tension device and blade holder are illustrated in Fig. 1 [8]. The device is designed in such a way that the test material can be held in biaxial tension by adjusting the lead screws of the clamping mechanism. Experiments were performed at a biaxial tension of 10 N. Although there is little data available on the magnitude of *in vivo* skin tension, 10 N is in line with the value of 5–24 N/m recorded by [13].

The knives most commonly used in stabbing incidents are those household knives which are most readily available [14]. Three knives commonly available in the household have been tested; a cook's knife, a carving knife and a utility knife (shown in Fig. 2). The blade tip geometry and the sharpness of the blade both play a major role in the amount of force used in stabbing incidents. For this reason it is important to capture the geometry of the blade accurately, in particular for the modeling of such geometries in a finite element analysis study. The blades were characterized by the following indicative dimensions; blade tip angle, blade tip radius, cutting edge angle and cross-sectional thickness (shown in Fig. 3). The cutting edge angle was measured using optical microscopes, while the blade tip radius and the blade tip angle were measured using Scanning electron microscope (SEM). The stab-penetration forces of three common non-blade implements were also investigated, i.e. a closed pair of scissors, a Phillips screwdriver and a flat head screwdriver.

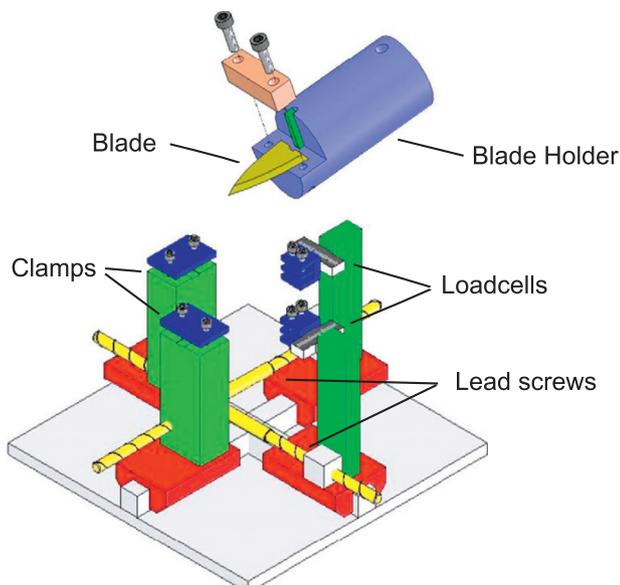


Fig. 1. Illustration of biaxial device.



Fig. 2. Selection of knives used in experiments. From top: utility knife, carving knife, cook's knife.

2.2. Finite element analysis

The accuracy of an FEA model is heavily dependent upon the accuracy and suitability of its material definitions. The Gasser-Ogden-Holzapfel (GOH) model is a popular structurally based strain energy potential that is commonly used to model the behavior of arteries [15,16]. The GOH model has been chosen here to model the behavior of skin. The material definitions used here have been evaluated directly using a combination of experimental testing and histological investigation of *in vitro* human skin in [17] and are provided in Table 1.

The failure mechanism employed is one of element deletion. In this method, once the stress in an individual element exceeds a specified threshold, the element is deemed to have failed and is deleted from the model. Here, the failure criterion is met when an element exceeds a Von Mises stress of 21 MPa, which corresponds to the ultimate tensile strength of human skin given in [18].

A further important aspect of the FEA model is the contact definition, i.e. how the materials in contact with each other will behave. The hard kinematic contact algorithm was chosen with finite sliding contact because it typically performs better when a hard surface, i.e. blade, contacts a much softer one, i.e. skin. The friction coefficient, μ , was chosen as 0.42 based on the findings of [19].

The geometry used to model the stab-penetration tests is shown in Fig. 4. Due to mirror symmetry, only one half of the cruciform, blade and substrate was modeled (the symmetry plane is in light gray in Fig. 4). A mesh convergence study was carried out to ensure that the chosen mesh was independent of further increases in mesh density. This check is particularly important for simulations which include element deletion, as element deletion is known to be susceptible to mesh dependency. It was found that at 8000 elements the solution was independent of further increases in the mesh density and this density using C3D8R elements was then chosen for use in all subsequent simulations.¹

3. Results

3.1. Target materials

The number of tests performed on human skin was limited. Therefore these tests can only be used to compare against the surrogate materials used, and to validate the developed FE model. Fig. 5 illustrates a typical force-displacement curve at quasi-static speeds for each of the three target materials: human skin, porcine skin and polyurethane. Examining only the shape of the curves, it can be seen that both the porcine skin and the human skin exhibit a non-linear curve within the range of the test, whereas the polyurethane does not. However, a clear advantage of using polyurethane over porcine skin as a surrogate material is that it eliminates the issue of biological variation.

3.2. Blade geometry

The three blades used for stab-penetration experiments were modeled using the characteristic blade dimensions given in Fig. 3. Each of these dimensions were quantified experimentally using SEM and microscopy. A selection of SEM images is shown in Fig. 6 and a summary of blade dimensions is given in Table 2.

¹ Further details of the FE model are available in [20].

Table 1
Material parameters of GOH model for skin (evaluated in [17]).

μ (MPa)	k_1 (MPa)	k_2	γ (°)	κ
0.2014	24.53	0.1327	41	0.1535

3.3. Presence of clothing

Stab-penetration tests were carried out on polyurethane at 100 mm/min with various layers of clothing present. For the four types of clothing tested (cotton, tracksuit, fleece, denim), we see an increase in penetration force varying from 10% for cotton to 50% for denim for a single layer of clothing. Two further tests were carried out with two layers of clothing, namely denim and cotton, and fleece and cotton. It was found that adding additional layers of clothing has an accumulative effect on the penetration force. Fig. 7 provides a graphical summary of these test results.

3.4. Test speeds

While at quasi-static speeds the influence of velocity was found to be insignificant in [8], here, where the test speeds were comparable to the maximum and mean velocities attainable during a stabbing incident [12,10], a clear effect can be seen when increasing the velocity. Fig. 8 compares the mean (\pm standard

deviation) maximum penetration force at quasi-static velocities, 1 m/s, 4.6 m/s and 9.2 m/s, for both polyurethane and porcine skin samples. An analysis of variance (ANOVA) revealed that test speed had a statistically significant effect on the penetration force ($P = 0.002$).

The decrease in penetration force between the quasi-static case and 1 m/s is due to the effects of viscoelasticity whereby the skin becomes stiffer at higher velocities. Since the skin is stiffer at the point of contact with the blade, the energy release rate increases, allowing the crack to propagate through the material more easily, resulting in a reduced rupture force [21]. Interestingly, while the mean penetration force at dynamic speeds was lower than that at quasi-static speeds, when we examine the dynamic speed tests alone, we see that with increased speeds, the force increases. Video analysis and FE simulations suggest that the increase at 9.2 m/s may be due to stress wave propagation through the material upon impact.

3.5. Implements

Fig. 9 compares the mean penetration force for each of the implements used, a closed pair of scissors, a flat-head screwdriver, a Phillips screwdriver, a cook's knife, a carving knife and a utility knife. Previous results indicated that the effect of varying the stabbing implement would have a significant effect on the force-displacement curve [3,4,8]. Our results support these findings, and

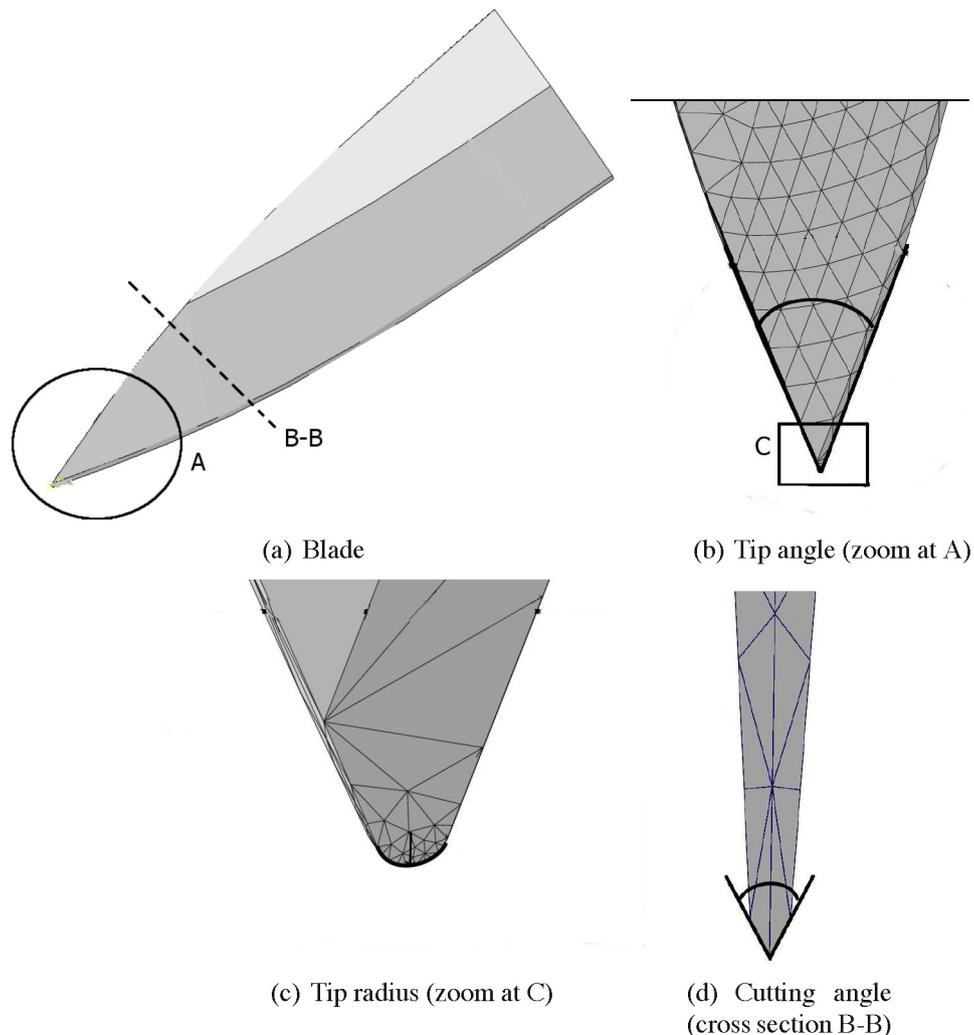


Fig. 3. Indicative blade dimensions.

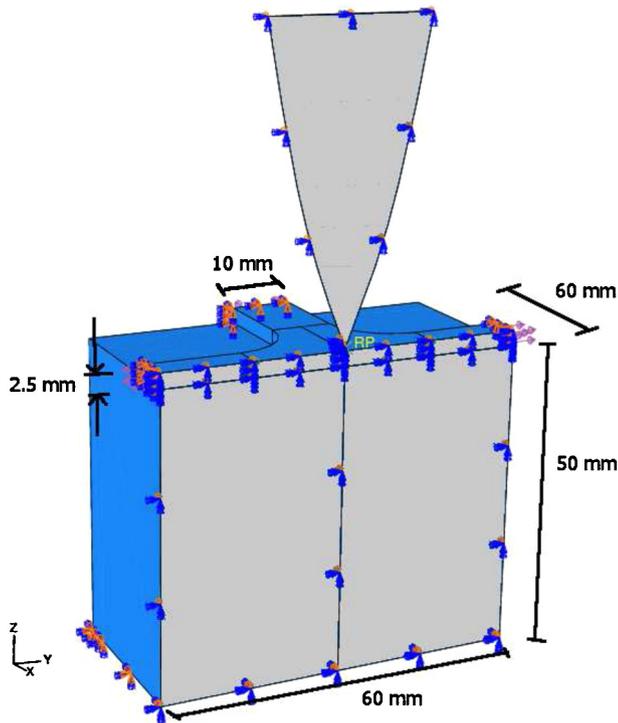


Fig. 4. Geometry and boundary conditions of model.

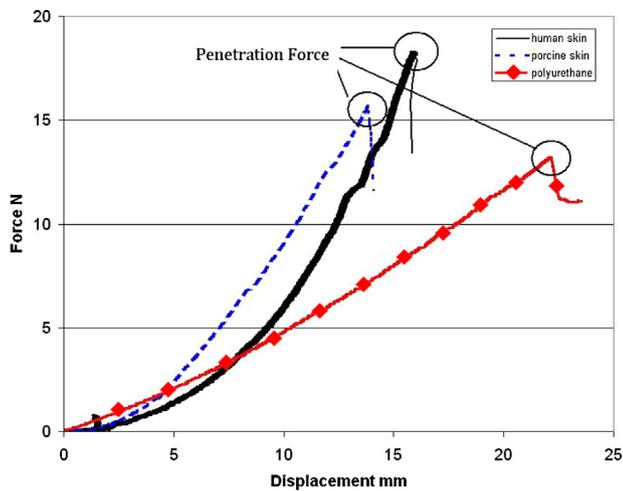


Fig. 5. Typical force-displacement curve of a stab-penetration test for each of the target materials at 100 mm/min using a carving knife.

Table 2
Summary of blade dimensions.

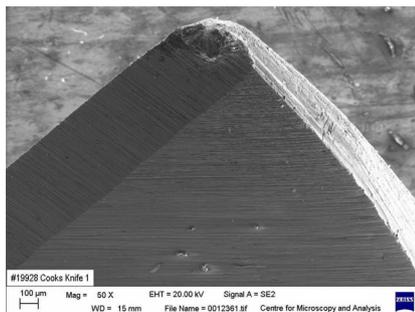
Dimension	Cook's	Carving	Utility
Tip angle (°)	53	35	45
Tip radius (μm)	210	125	120
Cutting angle (°)	47	50	53
Thickness (mm)	1.5	1.5	1

in particular those of [8] who found that of the three blades used (cook's, carving and utility knife), the cook's knife had the highest penetration force and the utility knife had the lowest. Comparing the penetration force of the blades to the non-blade implements, we see that these much blunter objects can exceed 300% the penetration force of a sharp blade. A further interesting result here is that the non-blade implements (scissors, flat head screwdriver, Phillips screwdriver) failed to puncture the skin or polyurethane at 1m/s, and simply rebounded off with no visible damage to the material.

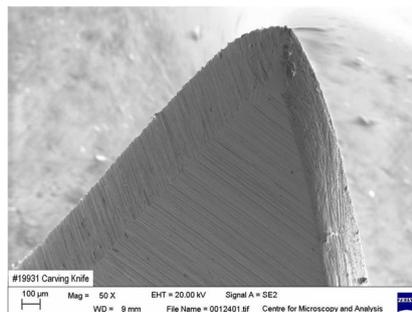
3.6. FE simulations

The element deletion process is shown in detail in Fig. 10. In Fig. 10 (a), the blade has deformed the skin but no initial penetration has occurred. This corresponds to the early portion of the force-displacement curve shown in Fig. 11. Once the threshold value of the failure criterion is reached, the top layer of elements is deleted and the blade then progresses to the next layer as shown in Fig. 10(b). The deletion of the top layer corresponds to a small drop in force-displacement curve in Fig. 11 (point B and C) until contact resumes again with the blade. This does not affect the maximum penetration force but leads to small intermittent decreases along the force displacement curve until rupture occurs. The blade progresses through the skin in this manner until full perforation of the skin occurs in Fig. 10(d), which corresponds to the maximum force shown at point D in Fig. 11.

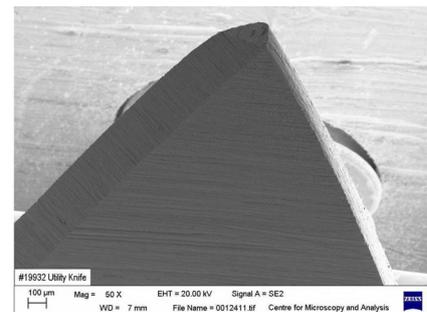
Examining in more detail the results of the FE model simulation, Fig. 11 compares the force-displacement graph predicted by the FE model against the corresponding experimental graph at quasi-static speeds for human skin. It can be seen that the FEA results offer an excellent match to the experimental data provided here. The maximum penetration force varies by only 1 N (6%) and while there is a difference of 2 mm (10%) between the maximum displacement values, it is comparable to the level of variation in the experimental results. It should be noted here that while the FE prediction is excellent at quasi-static test speeds, in its current form, it includes a hyperelastic material model of skin and therefore cannot capture the viscoelastic effects illustrated experimentally in Fig. 8.



(a) Side profile: cook's knife



(b) Side profile: carving knife



(c) Side profile: utility knife

Fig. 6. Scanning electron microscope images.

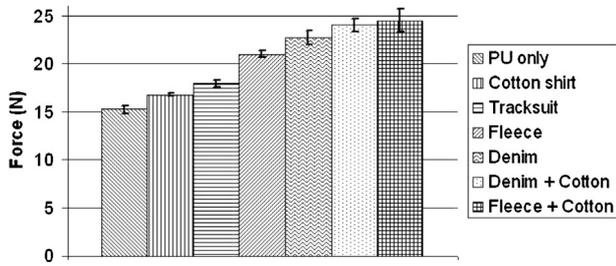


Fig. 7. The influence of the presence of various layers of clothing on the maximum penetration force during quasi-static stab-penetration experiments.

As further validation, Fig. 12 compares the maximum penetration force for each of the three blades and compares this to the experimental values. The magnitude obtained through simulation differs from the experimental mean, but it should be noted that the experimental results here are from tests on polyurethane and the numerical results are from human skin. The important point about this comparison, which is not like-for-like, is that the simulation results respect the experimental order of magnitudes, with the cook’s knife requiring the maximum force, followed by the carving knife and finally, the utility knife.

4. Discussion

The primary advantage of the present study over older studies which use an instrumented blade, is that the present experiments were carried out in a controlled and repeatable manner. Of course it is difficult to recreate the exact conditions of a knife attack in a laboratory setting, and the stab-penetration test is a simplified

model of such an attack. However, methods such as the drop-testing method employed here create good conditions for carrying out comparative studies to examine different blades, different approach speeds etc. [11]. Comparing our own results to those from the literature in Table 3 we see that the present experimental results are similar to those of [3] and [4], who used instrumented blades, and to those of [7] and [8] who used testing machines at quasi-static speeds. Our results appear to differ significantly only from the work of [6], whose forces appear to be substantially greater than all other authors.

The experimental aspect of this study was performed using human skin, porcine skin and polyurethane. Because the availability of human skin was limited, the majority of tests were performed using surrogate materials. There was, however, sufficient data available to conclude that both porcine skin and polyurethane are suitable surrogate materials for stab-penetration tests. Porcine skin mimics the behavior of human skin closely, having the same non-linear curve, anisotropy, and similar levels of deformation. The emphasis in this study has been placed on the puncture of skin alone, justified by the widely accepted fact that skin offers the largest protection to puncture until bone or cartilage is reached [3,4,6]. It is clear however, that the underlying tissue also plays an important role and cannot be ignored completely. For this reason, foam was placed below the target material to model the behavior of underlying soft tissue.

Previous authors have stated that the penetration force decreases as the speed is increased [3,4]. This effect is partly due to the viscoelastic nature of skin, which appears stiffer at higher velocities, but it is also influenced by fracture mechanics. Increasing the velocity of the blade increases the energy release rate of the skin, which results in a reduced rupture force [21]. This

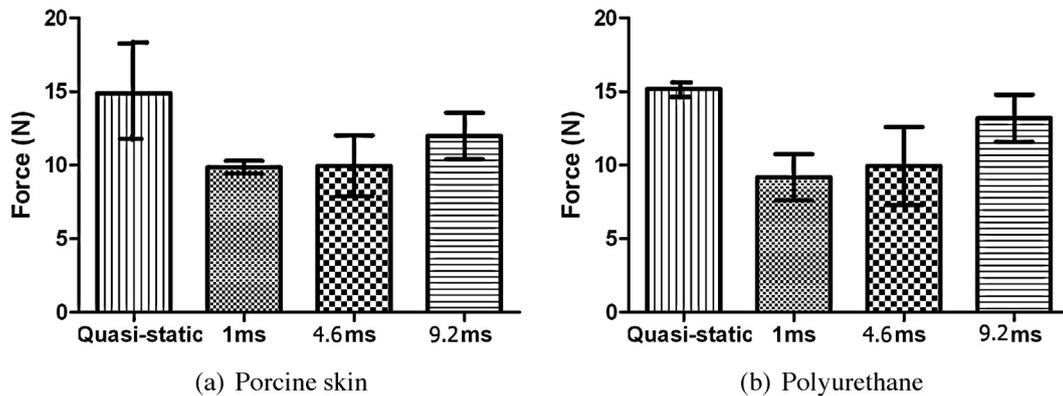


Fig. 8. Influence of test speed on penetration force of polyurethane and porcine skin using a cook’s knife.

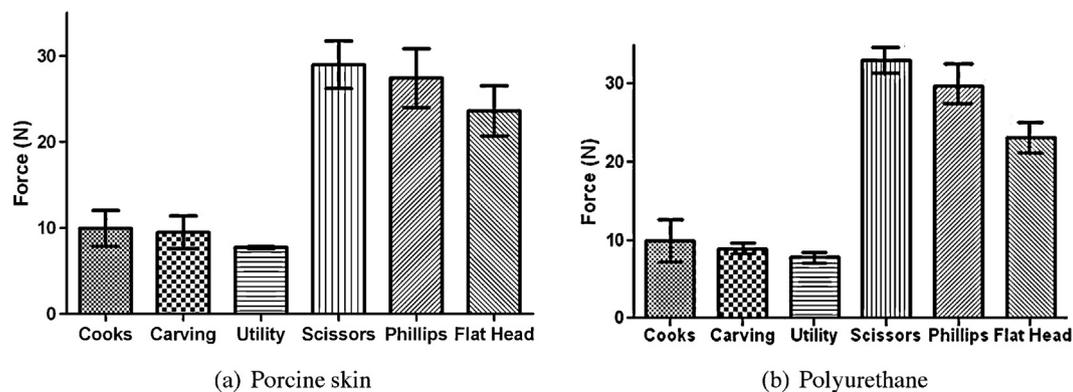


Fig. 9. Maximum force of various implements at 4.6 m/s.

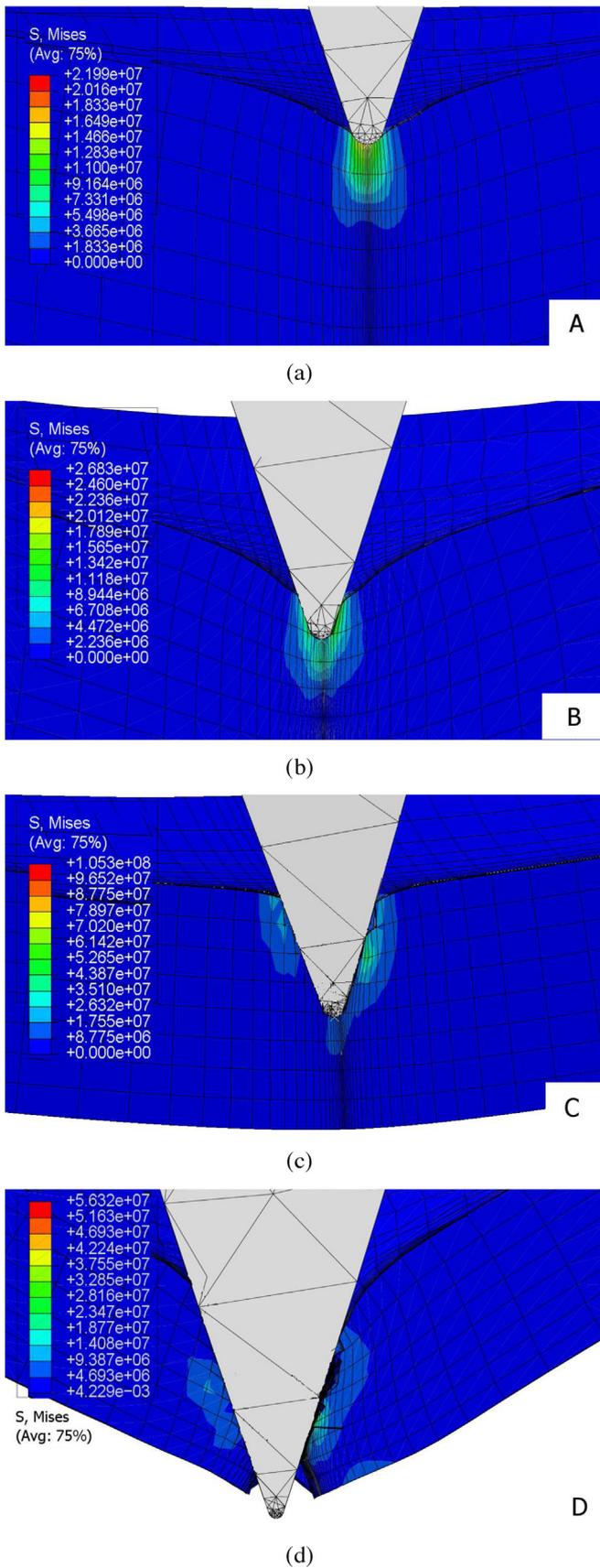


Fig. 10. Numerical progression of a carving knife through human skin (units in Pa).

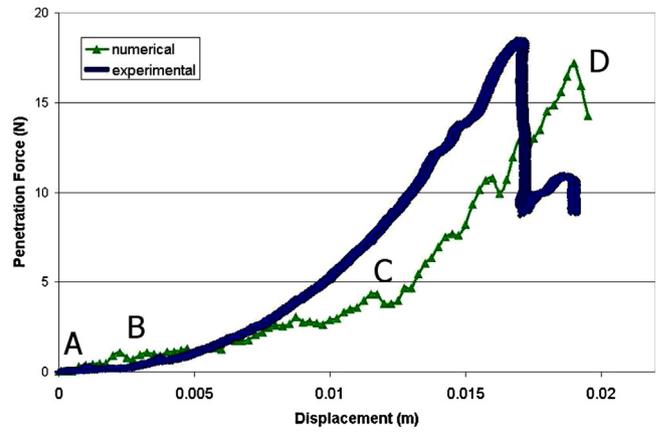


Fig. 11. Experimental and numerical force-displacement graph during stab-penetration test of human skin at 100 mm/min with a carving knife.

effect is related to the manner of crack propagation and is unique to highly deformable materials [21]. Increasing the velocity of the blade also leads to a reduced contact area between the blade and the skin [22]. Here, it has been shown that the penetration forces for dynamic tests overall are lower than the quasi-static tests, in agreement with [3,4]. However, it appears that at the 9.2 m/s speed, stress wave propagation in the material leads to a higher penetration force.

It is difficult to provide exact data on the details of clothing worn during stabbing incidents because in many stabbing case files there is no reference to the clothing worn. Nonetheless, a review of 108 stabbings in Ireland between 2000 and 2005 by [23] revealed that in 60 cases clothing was not available for examination, in 13 cases the clothing was examined and in the remaining 35 cases the clothing was examined and reported on in detail. Of these 35 cases it was found that 16 (46%) were wearing only a single layer of clothing, 15 (43%) were wearing two layers and 4 (11%) were wearing 3 layers. It has been shown experimentally that a single layer of clothing can increase the penetration force by up to 50% and future work should aim to include the effects of clothing layers in the FE model.

Previous authors have examined the effect of using various different blades and it is now well established that the blade tip-geometry has a significant effect on the penetration force [3,4,8,24,25]. Knight [3], in particular, has even examined the effect of using blunted blades. Our results found that such non-blade

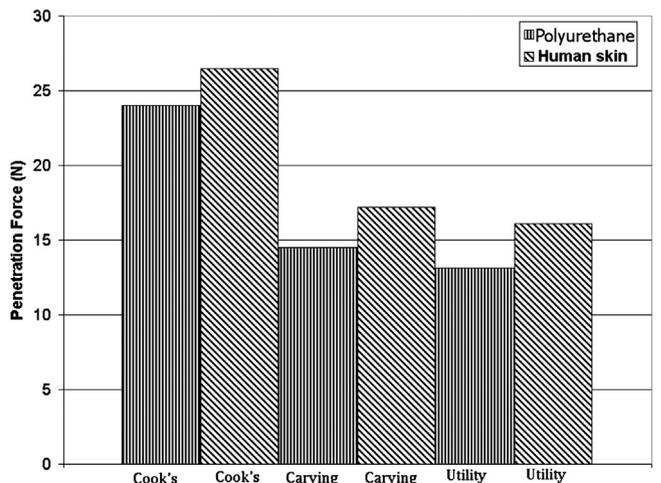


Fig. 12. Comparison of experimental (polyurethane) and numerical (human skin) maximum force for different blades at 100 mm/min.

Table 3
Summary of stab-penetration (with knives) results from the literature.

Author	Velocity	Target material	Force
[3]	Quasi-static, Dynamic	Cadaveric tissue	<5N for a sharp blade, 30–50N for a blunt blade
[4]	Quasi-static, Dynamic	Cadaveric tissue	<10N for naked skin, 70–100N for clothed
[6]	Quasi-static, Dynamic	Cadaveric tissue	35–55 N
[7]	Quasi-static	Porcine skin	10–15 N
[8]	Quasi-static	Polyurethane	13–20 N
Present results	Quasi-static, Dynamic	Cadaveric tissue, porcine skin, polyurethane	15–17 N at quasi-static, 10–12 N at dynamic

implements can exceed the penetration force of blades by 300%. Interestingly for forensic investigators, all of the non-blade implements failed to puncture the skin at 1 m/s. This places serious doubt over the validity of ‘walk-on’ style defenses where such non-blade implements have been used. Recently, [26] have quantified the penetration force for other implements such as screwdrivers using silicone gel and related the cross-sectional area of the screwdriver head to the penetration force. Here, we have identified three characteristic dimensions of a blade which affect the penetration force. A further publication [27] will utilize this fact together with the FE model developed here to devise a statistical model of stab-penetration force which could be used to predict the penetration force of a given blade.

5. Conclusion

The stab-penetration force of a variety of sharp implements has been experimentally determined using both human skin and suitable surrogates. Comparing the penetration force of the blades to the non-blade implements, it can be seen that these much blunter objects can exceed 300% the penetration force of a sharp blade. Similarly, the influence of the speed of attack has been investigated by examining a range of test speeds varying from quasi-static (50 mm/min) to dynamic (up to 9.2 m/s). An analysis of variance (ANOVA) revealed that test speed had a statistically significant effect on the penetration force ($P = 0.002$). Based on experimental material testing a finite element model has been developed which accurately reflects a stab-penetration event. The model prediction was found to be an excellent match to experimental stab-penetration tests. This FE model has been used in a further publication to develop a statistical model which could predict stab-penetration forces of a given blade.

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