



Biomechanics of knife stab attacks

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Abstract

Equipment, materials and methods for the measurement of the biomechanical parameters governing knife stab attacks have been developed and data have been presented that are relevant to the improvement of standards for the testing of stab-resistant materials. A six-camera Vicon motion analysis system was used to measure velocity, and derive energy and momentum during the approach phase of the attack and a specially developed force-measuring knife was used to measure three-dimensional forces and torque during the impact phase. The body segments associated with the knife were modelled as a series of rigid segments: trunk, upper arm, forearm and hand. The velocities of these segments, together with knowledge of the mass distribution from biomechanical tables, allowed the calculation of the individual segment energy and momentum values. The instrumented knife measured four components of load: axial force (along the length of the blade), cutting force (parallel to the breadth of the blade), lateral force (across the blade) and torque (twisting action) using foil strain gauges. Twenty volunteers were asked to stab a target with near maximal effort. Three styles of stab were used: a short thrust forward, a horizontal style sweep around the body and an overhand stab. These styles were chosen based on reported incidents, providing more realistic data than had previously existed. The 95th percentile values for axial force and energy were 1885 N and 69 J, respectively. The ability of current test methods to reproduce the mechanical parameters measured in human stab attacks has been assessed. It was found that current test methods could reproduce the range of energy and force values measured in the human stab attacks, although the simulation was not accurate in some respects. Non-axial force and torque values were also found to be significant in the human tests, but these are not reproduced in the standard mechanical tests. © 1999 Elsevier Science Ireland Ltd. All rights reserved.

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1. Introduction

In a recent study of assault victims presenting at an Accident and Emergency unit in the West of Scotland, it was found that penetrating weapons had been used in 23% of the 235 cases reported in a 2-month period [1]. In another study, in London, knives had been used in 15% of assaults, and accounted for 90% of the serious injuries [2]. The need for police officers attending incidents of serious assault to be afforded protection is obvious, yet few suitable garments are on offer. Body armour designed for anti-ballistic use is not necessarily resistant to penetration of blades and armour specifically designed to withstand blade penetration is prohibitively bulky and heavy. The development of stab-resistant body armour has been a low priority for manufacturers until now as makers are largely based in the USA, where police officers are more likely to face the threat of shooting than stabbing [3].

To design suitable new garments that will offer the desired level of protection without being prohibitively bulky, accurate knowledge of the level of threat posed by a knife attack is needed. Information in the literature about the mechanics of knife stab attacks is scarce. Knight [4] examined the force necessary to penetrate the human skin in the context of medico-legal cases, and found that a force of as little as 5 N was sufficient with the sharpest of knives. A similar study, using porcine tissue, was carried out by Jones et al. [5], who stated that forces in excess of 250 N failed to achieve penetration of the skin using a blunt knife. Calvano [6] conducted a study into the most important factors affecting penetration of soft armour, using forces of up to 800 N. There is no evidence in the literature, however, to compare this figure to a real life situation. A recent kinematic study of stab attacks, using two-dimensional video analysis, reported mean approach velocity for an overhand style to be 12 m/s, and that for a thrust style to be 6.6 m/s [7]. In that study, the target was freely suspended and the mass of the knife was 192 g.

The current test standard used by British manufacturers has been developed by the Police Scientific Development Branch (PSDB) and is based on a 400-g knife being fired into the target material from an air-cannon, with energies ranging from 20 to 65 J [8], giving impact velocities from 10 to 18 m/s. Success or failure of the armour material is judged on a sliding scale of allowable penetration. The equivalent US test requires the material to completely resist penetration with an awl at 110 J [6], illustrating the diversity of standards in current use.

The present study aims to provide scientifically verified data on the characteristics of human knife stab attacks, allowing the development of more realistic test procedures for stab-resistant materials than the current methods. To this end, a range of parameters relevant to knife stab attacks has been measured. These include velocity, energy and momentum of the attacker and knife and the three-dimensional forces and torque applied to the target. The ability of the current drop-tower tests to replicate human knife stab attacks has been assessed using a telemetry-based force-measuring knife.

2. Methodology

The human stab attack was divided into two stages for convenient description and analysis. The first of these was the approach phase, ending when the knife tip first touched the target and the second was the impact phase, from the end of the approach phase to the point when the knife was brought to rest by the target.

2.1. Motion analysis

The approach phase was analysed using a six-camera VICON motion analysis system (Oxford Metrics, Oxford, UK). The cameras emit pulsed infrared light at 50 Hz and the light reflected back from markers placed on the subject then forms an image in the field of view of the camera. If the images from two or more cameras are combined, the three-dimensional position of the marker in the laboratory space can be reconstructed. Combining sequential frames of marker positions allows the trajectories of the markers to be recorded.

The body segments associated with the knife were modelled as a series of rigid segments: trunk, upper arm, forearm and hand. Each segment, and the knife, was marked with a cluster of three markers, enabling three-dimensional motion to be tracked (see Fig. 1). The calculation of the velocities of these segments, and knowledge of the mass distribution from biomechanical tables, allowed the calculation of the segment energy and momentum values.



Fig. 1. A volunteer performing an overhand stab, showing the force-measuring knife and marker positions.

2.2. Force measurement

A specially developed force-measuring knife was used to measure the parameters of interest during the impact phase. No motion analysis was possible during this phase as the acceleration values were beyond the capabilities of the Vicon system. The knife was designed to measure four components of load: axial force (along the length of the blade), cutting force (parallel to the breadth of the blade), lateral force (across the blade) and torque (twisting action). The active part of the transducer consists of an aluminium alloy cylinder of inner diameter 21 mm and outer diameter 24 mm on which electrical foil strain gauges are mounted (Fig. 2). A brass boss was pressed into the end of this to allow fixture of the knife blade. This assembly then fits into the outer handle. For safety reasons a padded hilt of diameter 90 mm is located at the base of the handle. The device was calibrated using an Instron Materials Testing Machine and using calibrated, dead weights. The calibration allows for the presence of cross-talk between channels and results in a matrix which is used to calculate load from an array of signals.

Data from the instrumented knife were sampled at 2500 Hz, the maximum possible with the Vicon software. Subsequent minor processing to take account of any calibration cross-effects produced the magnitudes of the four components of applied load.

2.3. Test programme

Twenty volunteers, comprising students and members of the local Police force, were asked to stab a target with near maximal effort. The volunteer group consisted of 17 males and three females, their body masses ranged from 54 to 98 kg, and their heights varied from 1.63 to 1.98 m (mean, 79.6 kg, 1.789 m). Three styles of stab were agreed upon following consultation with police authorities: a short thrust forward, a horizontal style sweep around the body and an overhand stab. The subjects performed five stabs for each style with two different levels of target backing compliance, totalling 30 stabs per

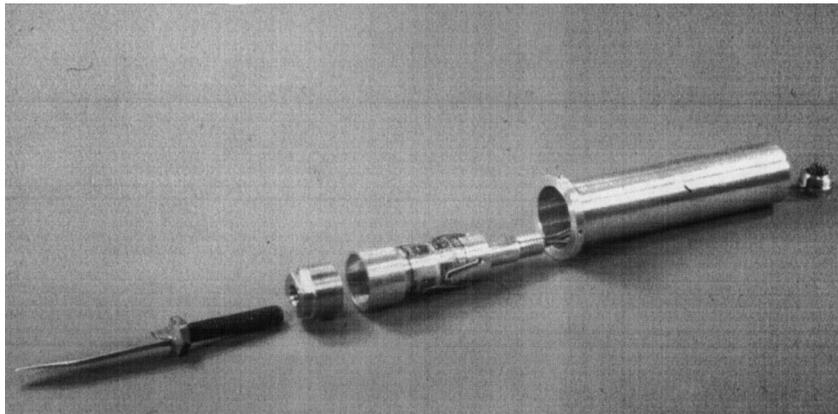


Fig. 2. An exploded view of the force-measuring knife. the central component shows the strain gauge positions.

subject. The target was positioned vertically for the thrust and sweep and inclined at 30° back from the vertical for the overhand stab. The subject was asked to adopt a natural action within the stab styles defined. All equipment and procedures were approved by the Bioengineering Unit's Safety Committee and the University Ethics Committee.

2.4. *The target*

The target consisted of a box containing Plastilina® (Roma Plastilina® No.1, Jolly King Sculpture Accessories, USA), previously used in stab simulation tests and intended to simulate the compliance of human flesh, covered with a sample of stab-resistant material. Following preliminary trials, it was thought that the Plastilina® did not sufficiently mimic the flesh and thus a piece of foam of density 33 kg/m³ and thickness 30 mm was placed between the box and the material for 50% of the tests. Calvano [6] used foam of density 35 kg/m³ to simulate resistance of the human body. The stab-resistant material was made up of 28 layers of Kevlar® 0.3 mm thick, in a 1.4-mm pitch weave, arranged in two groups of 14, backed by two sheets of polypropylene of thickness 1.0 mm, covered with tightly woven nylon. The overall thickness was 10 mm.

2.5. *Correlation with drop tower*

To assess the ability of the current drop-tower (or air-cannon) test to replicate the forces found in human stab attacks, a telemetry-based force-measuring knife was built for use in the drop-tower. This is a single-channel strain gauge device, housing a strain gauge amplifier and radio transmitter, allowing the axial force on the knife blade at impact to be recorded (Fig. 3). The receiver and data collection equipment can then be operated at a safe distance from the tower without the need for trailing leads, which are unsatisfactory in dynamic and impact situations. The momentum and energy of the knife were varied by varying the mass of the knife holder and the height from which it was dropped. Tests were carried out with three different masses and three starting heights. Three trials at each combination of velocity and mass were taken. All trials were completed without the foam backing used in volunteer tests, in keeping with current testing practice.

3. Results and discussion

The data from the motion analysis are summarised in Table 1. The amount of energy the volunteers were able to generate in a stab attack covered a wide range of values, exceeding 100 J at the highest level. The values appear to be influenced by the style of approach, with the sweep producing the highest values, followed by the overhand and finally the thrust. The values of momentum encountered were also high, with 60 kg·m s⁻¹ being exceeded in some cases with every style. The effect of style on momentum values followed the same pattern as that for energy.

The results of the post-impact phase of the analysis are seen in Table 2. The force along the blade (axial force) often reached values in excess of 2000 N. Again, some

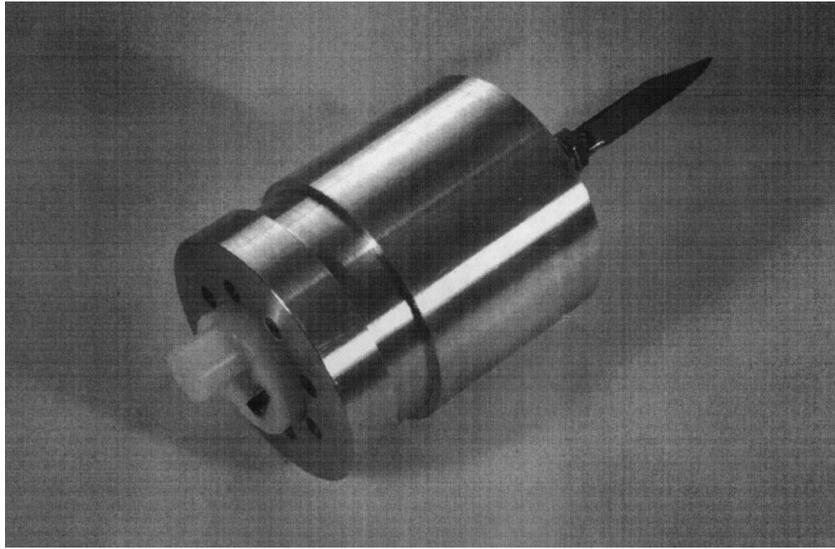


Fig. 3. The telemetry-based force-measuring knife after final assembly.

Table 1
Summary of results from the approach phase (volunteer tests)

| | Velocity (m s^{-1}) | Momentum ($\text{kg}\cdot\text{m s}^{-1}$) | Energy (J) |
|-----------------|--------------------------------|--|------------|
| Minimum | 2.6 | 12 | 7 |
| Mean | 5.8 | 40 | 36 |
| 95th percentile | 8.4 | 68 | 69 |
| Maximum | 9.2 | 104 | 103 |

influence of style was seen on the forces generated, with the overhand stab tending to produce the largest forces and the thrust producing the smallest values. The cutting force and lateral force values were also found to be large in some cases, and were noticeably style dependent. The highest cutting forces were found with the overhand style, where the action tends to drag the knife down, and had a median value of approximately 300 N. Lateral force values tended to be highest during the sweep style of stab, but were generally lower than the cutting forces. The measured torques, or twisting effects, were also highest during the sweep. Fig. 4 shows the combined load effects acting on the

Table 2
Summary of results from the impact phase (volunteer tests).

| | Axial force (N) | Cutting force (N) | Lateral force (N) | Torque (Nm) |
|-----------------|-----------------|-------------------|-------------------|-------------|
| Minimum | 474 | 18 | 14 | 0.4 |
| Median | 1091 | 146 | 88 | 2.6 |
| 95th percentile | 1885 | 465 | 343 | 6.6 |
| Maximum | 2261 | 869 | 634 | 9.4 |

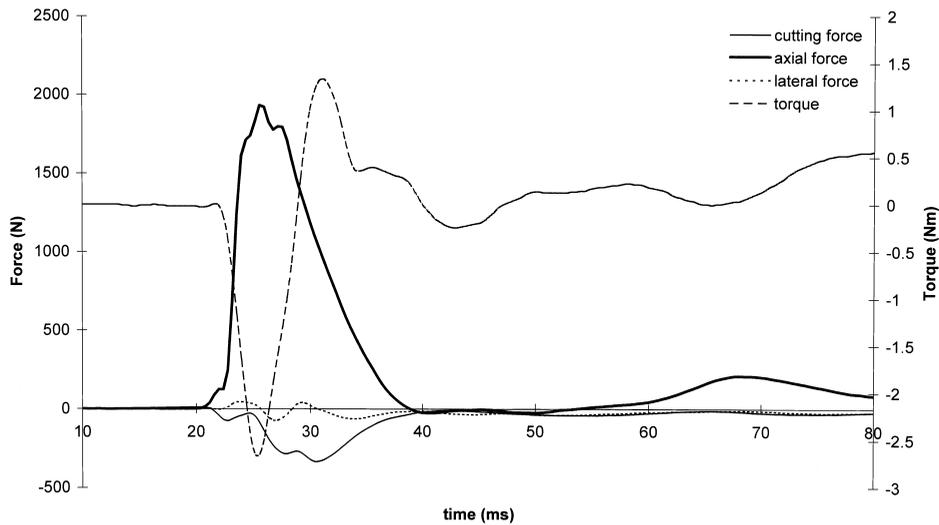


Fig. 4. Force–time profiles for the four measured components of load on the instrumented knife (volunteer test, overhand style).

knife for an overhand style stab attack, indicating that the maximum values for the four components of load do not necessarily occur simultaneously.

Following concerns about the viability of Plastilina[®] to simulate the human body in the body armour tests, a further study was commissioned to develop a new simulant that more closely matched the compliance of the human body. The results of the volunteer tests using the new simulant reduced the measured median axial force values by 15% and the 95th percentile values by 9%.

The results of this study suggest that it may be impractical to design a garment that will protect against every possible threat, since in such a case the garment might be unwearable. Consultation with police forces also suggests that different levels of protection are required in different scenarios and that in some situations the garment would need to be worn covertly. There is thus a decision to be made about the level of protection to provide, and clustering the results according to percentiles allows this to be done. For example, although the energy exceeded 100 J in one case, 95% of values were below 70 J and 50% were below 40 J.

Although the values obtained during the volunteer tests were very high, it must be realised that these values represent the maximum threat the wearer of an anti-stab garment is likely to face. This is because the cross-section of volunteers used in the study was dominated by large, strong police officers trained in the skills of self-defence, the instrumented knife, having a relatively large handle diameter and a padded hilt, allows for the production of higher forces than may be found with a more typical attack weapon and the target was rigidly mounted. One factor that could work in the opposite direction, however, is the fact that none of the volunteers was in a state of fear, rage or excitement, which could tend to increase physical performance.

Table 3 and Fig. 5 present the results of the drop-tower tests. The combinations of

Table 3

A summary of the force values measured in drop-tower tests at different levels of energy and momentum

| Mass (kg) | Impact velocity (m s ⁻¹) | Energy (J) | Momentum (kg·m s ⁻¹) | Peak force ^a (N) |
|-----------|--------------------------------------|------------|----------------------------------|-----------------------------|
| 4.5 | 5.4 | 66.2 | 24.4 | 2116 |
| 4.5 | 7.0 | 110.4 | 31.5 | 2688 |
| 4.5 | 9.4 | 198.7 | 42.3 | 2979 |
| 1.9 | 5.4 | 28.0 | 10.3 | 869 |
| 1.9 | 7.0 | 46.6 | 13.3 | 1772 |
| 1.9 | 9.4 | 83.9 | 17.9 | 2515 |
| 1.0 | 5.4 | 14.7 | 5.4 | 511 |
| 1.0 | 7.0 | 24.5 | 7.0 | 882 |
| 1.0 | 9.4 | 44.1 | 9.4 | 996 |

^a Average of three trials.

velocity and mass used in the tests were chosen to try to replicate the range of values found in volunteer tests. Although it is possible to replicate the magnitude of the axial force produced in human stab attacks with the drop-tower, the profile of the force–time curve is different. In most cases in the human attack, the force profile has two peaks (Fig. 6). This may be due to the fact that there is some delay between the knife coming to rest and the soft tissue of the arm coming to rest. In the drop-tower test, there is only one peak and this may be a serious shortcoming in terms of simulating blade penetration. It is also difficult to introduce cutting and lateral forces together with torque, in a simple drop-tower test.

With the current drop-tower design, it can be seen that, while the range of velocity, energy and momentum can be reproduced, it is impossible to match the combination of all three to the human case. It is possible to match only two of the three: energy and

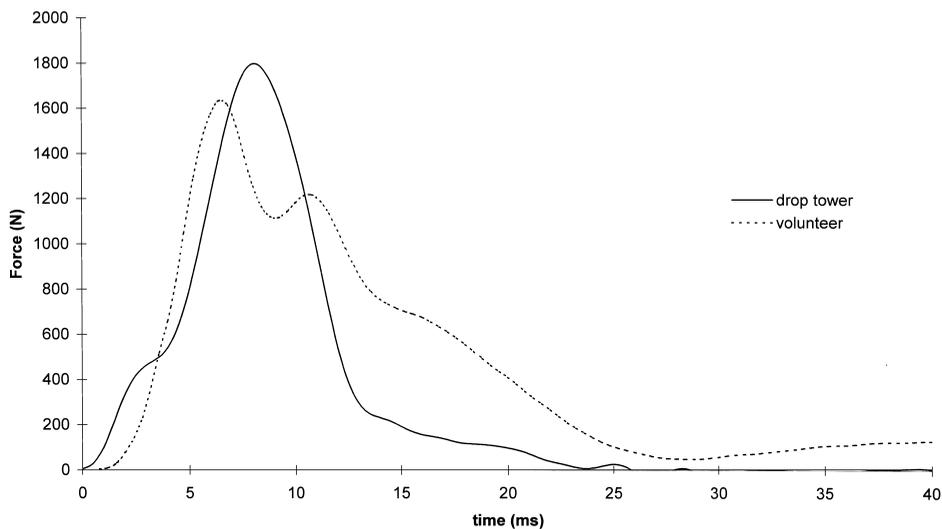


Fig. 5. A comparison between the axial force–time profiles of the drop-tower test and the volunteer test.

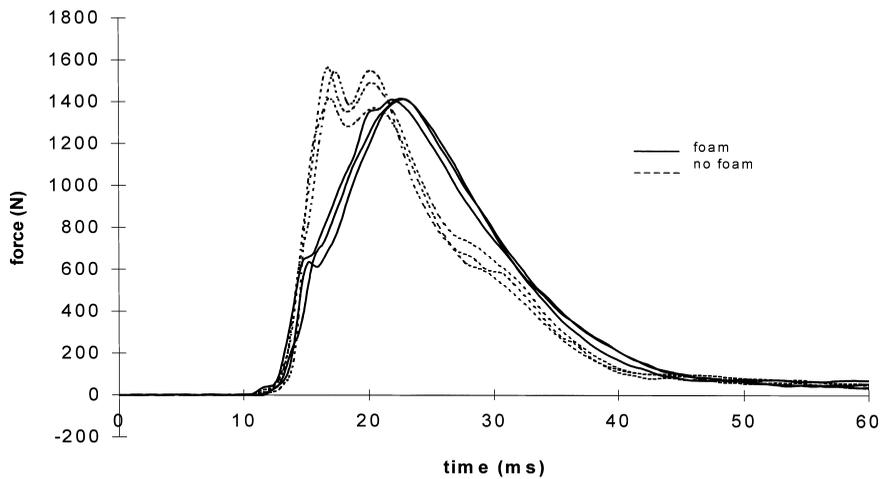


Fig. 6. The effect of placing a layer of foam between the stab-resistant material and its backing on the axial force–time profile (volunteer tests).

momentum, energy and velocity or momentum and velocity. This is because in the human stab the energy and momentum measured are made up of several different masses travelling at different velocities, whereas the drop-tower has only one mass in motion. Due to the dimensional limitations of mass, the momentum values tended to be small compared with those seen in volunteer tests, for a given energy value.

4. Conclusions

This study has successfully developed equipment, materials and methods for comprehensive evaluation of the mechanics of knife stab attacks. A group of volunteers has been measured performing simulated stab attacks and the governing parameters have been measured. These show that energy values of over 70 J are regularly seen during the approach phase and that force values of over 2000 N are seen during impact on targets with compliance matched to that of the human body.

The ability of a uni-axial drop-tower or air-cannon test to simulate the effects of a human stab attack has been assessed and found to be less than ideal. It has also been found that the simulant used to support the material under test has a significant influence on the force values measured. Important new data have been presented which will allow the development of more realistic testing procedures for stab-resistant body armour.

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