RESEARCH ARTICLE

Peak Penetration Force during Stabbing of Chest Wall with a Ceremonial Sword

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ARTICLE HISTORY

Received: July 20, 2023
Revised: November 10, 2023
Accepted: November 21, 2023

DOI:
10.2174/0126664844267345240105094842

Abstract: ***Background*:** The force required for a sword to penetrate the human chest was identified as an important issue for the defense in a case of homicide by stabbing. Previous literature on penetration force had tested knives but not swords.

***Objective*:** The objective of the current study was to determine the peak force during penetration of a surrogate for human tissue with a ceremonial sword.

***Methods*:** The sword was secured to an MK-10 Tensile Tester and forced to penetrate a pork rib cut at speeds of 350 mm/min and 1100 mm/min, including both regions of rib and cartilage for pork ribs without skin or covered with a layer of porcine skin.

***Results*:** In the case of the pork ribs without skin, the mean peak penetration force at a speed of 350 mm/min was 11.0 N compared to a mean of 10.5 N at a speed of 1100 mm/min. The distributions of peak penetration forces at the two speeds were not significantly different. In the case of the pork ribs covered with porcine skin, the mean peak penetration force at a speed of 350 mm/min was 50.0 N compared to a mean of 47.6 N at a speed of 1100 mm/min. The distributions of peak penetration forces at the two speeds were again not significantly different.

***Conclusion*:** Forces of less than 50 N would be required for a ceremonial sword to penetrate the tissues of the human chest, although there is a risk of penetration for forces as low as 5 N when the effect of the porcine skin is not considered. Furthermore, the force required for penetration did not vary significantly over a three-fold speed of penetration.

Keywords: Sword, stabbing, penetration force, chest, skin.

1. INTRODUCTION

Fatal stab wounds in homicides most frequently involve penetration of the anterior chest region [1-7]. Such stab wounds are generally inflicted with a sharp object such as a knife. A number of studies have investigated the force required to penetrate the skin or skin simulants with sharp objects [8-17]. In one set of studies, chest penetration forces were measured in human cadavers [9, 10]. The forces required to penetrate the chest were determined for three types of knives, namely serrated steak knife, butcher's knife and lock blade knife. The penetration speed was controlled with an MTS system set to 0.1 m/s. The average peak force required to penetrate the skin was similar for the three knives, ranging from 23.0 N to 26.3 N. However, there was a greater variation in the average peak force required to penetrate cartilage, ranging from 68.9 N to 126.5 N, with the highest value recorded for the steak knife. Pork ribs have also been used as a surrogate for the human chest in knife penetration tests, although without the overlying skin layer [11, 12]. Average penetration forces for an all-purpose knife and a serrated steak knife, tested with an MTS system, ranged from 12.0 N to 41.9 N, again with the highest force recorded for the steak knife [11]. Tests with a custom ground double-edged blade produced peak penetration forces of porcine skin in the range of 12.5 N to 13.2 N [15]. Overall, these results suggest that the type of knife and the material properties of the tissue are important factors in determining the magnitude of the force required to penetrate the chest. Furthermore, geometric factors such as tip angle, tip radius, cutting edge angle and blade thickness influence the required penetration force [14, 16].

The dependence of skin penetration force on the speed of penetration has been tested on porcine skin, in the process of developing a numerical model for stab penetration force [16]. The peak penetration force was found to vary in a non-linear manner with penetration speed. Peak penetration force using a cook's knife was approximately 15 N for quasi-static penetration (100 mm/min), 10 N at 1 m/s and 4.6 m/s and approximately 12 N at 9.2 m/s. Peak penetration forces varied in a similar manner for a carving knife

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and a utility knife, although the magnitude was slightly lower for the utility knife. Because blade and tip characteristics of knives can vary significantly, the results of tissue penetration tests carried out with one type of blade cannot be used to accurately infer the force required to penetrate the same tissue with a different type of blade, *i.e*. tests for penetration force should be carried out with the knife specific to the incident being investigated.

In particular, the results of tests conducted with common household knives are not suitable for inferring the force required to penetrate tissue with a sword. Although swords are generally designed more for slashing than stabbing, swords have been used as murder weapons in stabbings [18-20]. In investigating a recent case in which a ceremonial sword inflicted a fatal chest wound, the question arose as to the force necessary to penetrate the soft tissue of the thorax. A study was conducted that employed elements of previous studies conducted with household knives [10, 11].

2. MATERIALS AND METHODS

A pork spare rib cut was used as a surrogate for the soft tissue of the human chest [11, 12]. The spare rib cut represents the tissue near the belly of the animal where the ribs border cartilage. This anatomical location was considered to best correspond to the human anatomy where the sword entered the victim's chest. The spare ribs were supported on a sheet of 3/4" plywood with a circular hole beneath the ribs, at the location of sword penetration. The hole was large enough to allow passage of the sword through the thickness of the spare ribs. The incident ceremonial sword (Fig. **1**) was acquired for testing and securely clamped to the moving fixture of a Mark-10 Tensile Tester as shown in Fig. (**2A**). The Tensile Tester was programmed to record the peak force as the sword penetrated the spare ribs. Two spare rib samples without skin were subjected to sixty penetrations, 30 at a speed of 350 mm/min (0.0058 m/s) and 30 at a speed of 1100 mm/min (0.0183 m/s). An example of penetrations to one spare rib sample is shown in Fig. (**2B**). A third spare rib sample covered with a 6 mm thick strip of porcine skin was subjected to 36 penetrations, 18 at a speed of 350 mm/min and 18 at a speed of 1100 mm/min.

Fig. (1). Incident ceremonial sword. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

3. RESULTS

The mean peak penetration force for the spare rib samples without skin at 350 mm/min was 11.0 N (standard deviation 6.9 N) compared to 10.5 N (standard deviation 5.1 N) at 1100 mm/min. The Shapiro-Francia test was first applied to the data to test whether the distributions were normal. Based on the Shapiro-Francia test, the distributions were found to differ significantly from normal distributions. Therefore, the Wilcoxon signed-rank test was used to determine whether the peak forces obtained with the 350 mm/min penetration speed were significantly different from the peak forces obtained with the 1100 mm/min pentation speed. The Wilcoxon signed rank test indicated that there was no significant difference between the peak forces at the two penetration speeds (p=0.85).

The mean peak penetration force for the spare rib sample covered with porcine skin at 350 mm/min was 50.0 N (standard deviation 8.9 N) compared to 47.6 N (standard deviation 4.5 N) at 1100 mm/min. The distribution at the higher penetration speed was found to differ significantly from normal based on the Shapiro-Francia test. However, the Wilcoxon signed rank test indicated that there was no significant difference between the peak forces at the two penetration speeds (p=0.28).

Fig. (2). (**A**) MK-10 Tensile Tester shown with clamped ceremonial sword, illustrating position of sword tip prior to penetration of pork rib cut. (**B**) Example of four penetration wounds where each parallel pair represents a penetration at 350 mm/min and a penetration at 1100 mm/min. (*A higher resolution/colour version of this figure is available in the electronic copy of the article*).

Although the penetration forces are not normally distributed, the normal distribution, corresponding to the mean and standard deviation of the entire data set was calculated and plotted for comparison for the pork ribs without skin (Fig. **3**) and the pork ribs covered with porcine skin (Fig. **4**). The result suggests that 50% probability of penetration with the ceremonial sword would occur at approximately 11 N and forces above 30 N would create a risk of penetration of almost 100% for the pork ribs without skin whereas

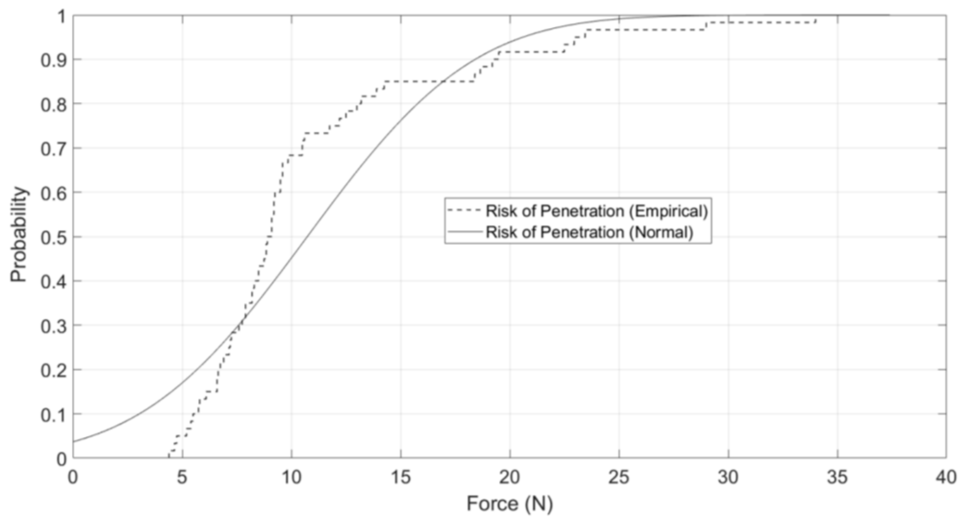

Fig. (3). Risk of penetration for pork ribs without skin with the theoretical normal distribution of forces (solid line) overlaid on the empirical data from penetration tests (dashed line).

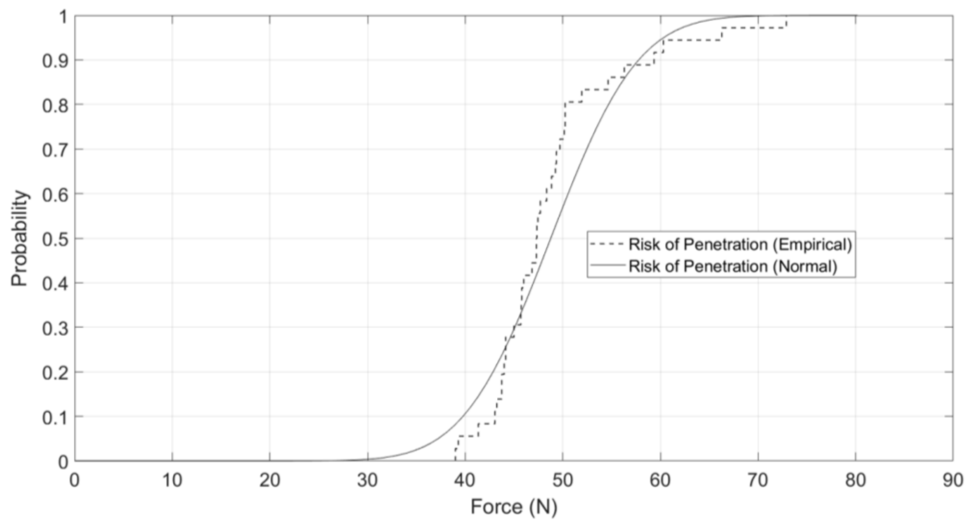

Fig. (4). Risk of penetration for pork ribs covered with porcine skin with the theoretical normal distribution of forces (solid line) overlaid on the empirical data from penetration tests (dashed line).

when the ribs are covered with porcine skin, 50% probability of penetration would occur at 49 N and forces above 70 N would create a risk of penetration of almost 100%.

One penetration was attempted through the bone at a speed of 350 mm/min. The penetration reached a force of 140 N, after penetrating the bone to a depth of approximately 2 mm.

4. DISCUSSION

The pork rib cut used in our penetration tests consisted principally of muscle and connective tissue, *i.e*. cartilage. The results indicate that there is a similar variation in peak force for different penetration speeds and that the peak force does not vary significantly with speed. The variation in peak force was similar for tissue between the ribs and regions consisting principally of cartilage. The low values of peak penetration force indicate that the tip of the ceremonial sword must be relatively sharp. The mean peak force of 11 N at a penetration speed of 350 mm/min is similar to that of an all-purpose Sabatier knife, found to be approximately 12 N, on average, when penetrating similar tissue [12]. In that study, five different exemplars of the same knife were used and it appears that each knife was only tested in a single trial without indicating the precise location of penetration. Larger penetration forces were reported with a serrated steak knife, with an average peak penetration force of approximately 42 N. This is somewhat higher than the largest peak penetration force recorded in our tests with the ceremonial sword, which was 34 N. Thus, we can infer that the tip of the incident ceremonial sword is likely sharper than a steak knife but similar to an all-purpose Sabatier knife.

We found that the force required to penetrate porcine skin was considerably higher than that required to penetrate the pork rib samples without skin, although the results of tests conducted in a previous study [16], suggest that a much lower force is required to penetrate porcine skin than in our tests. The mean peak force for penetrating porcine skin at a speed of 100 mm/min in the previous study was found to be approximately 15 N using a cook's knife. Penetration of porcine skin was compared to penetration of human skin samples and it was found that porcine skin closely mimics the mechanical properties of human skin. The higher penetration forces in our tests may be explained by the difference in protocol. First, the porcine skin in our tests was approximately 6 mm thick compared to 2 mm in the previous study. Second, a rectangular strip of porcine skin was draped over the pork rib sample without fixation in our tests, whereas in the previous study, the porcine skin was cut to a cruciform shape, clamped with a tension of 10 N and supported by polyethylene foam. Since the skin was allowed to go slack in our tests, it is likely that it underwent considerably more compression prior to the onset of penetration than in the previous study, *i.e*. the tip of the sword would not have begun penetrating the tissue until the force was considerably higher than if the porcine skin had been held in tension. In addition, the sword had to penetrate skin which was three times as thick as in the previous study.

Much higher penetration speeds, ranging from 1 m/s (60,000 mm/min) to 9.2 m/s (552,000 mm/min), were also tested in the previous study [16], demonstrating that the peak penetration force dropped when the penetration was no longer quasi-static, although, at the highest penetration speed, it again approached the quasi-static value. In another study, using a purpose-built double-edged blade with a penetration speed of 480 mm/min [15], the penetration force for porcine skin ranged from 12.5 N to 13.2 N. Again, in that study, the thickness of the porcine skin was approximately 2 mm and the skin sample was clamped all around with a steel plate, which would have placed the skin in tension, likely accounting for the lower penetration force than in our tests. It is, therefore, more likely that the force required for penetration of the ceremonial sword through skin would be more similar to the forces that we measured during penetration of the pork rib cut without skin than the forces that we measured when porcine skin covered the pork ribs.

The primary objective in testing the penetration force of the ceremonial sword was to determine the minimum amount of effort required to produce the fatal chest wound. The penetration forces measured in our tests corresponded closely to those recorded in penetration tests on similar tissue with an all-purpose Sabatier knife [11], which was most similar to the cook's knife used in tests on human and porcine skin samples [16] and the butcher's knife used in the tests conducted on human cadavers [10]. The mean peak penetration forces measured during penetration of the skin and cartilage in the chest region of human cadavers at 0.1 m/s (6000 mm/min) [10], were higher than those measured in studies with porcine tissue, both at lower and higher penetration speeds. Penetration tests with various types of knives have also been conducted on pork loin tissue with intact overlying skin and fat layers [8]. In that study, the penetration speed was 1 m/s (60,000 mm/min) and penetration forces of 25 N to 26.5 N were measured for a serrated knife and 36 N to 37.8 N for a utility knife. In another study, the peak force applied to an instrumented knife was measured during a 10 cm penetration into the thigh of human cadavers [17]. Although the penetration speed and type of knife were not specified, the recorded forces were similar to those recorded when a steak knife was used to penetrate pork leg at 0.1 m/s (6000 mm/min), but higher than forces recorded when a Sabatier all-purpose knife was used [11]. Thus, the difference in force measured during knife penetration of human cadavers may be partially due to differences in the mechanical properties of the tissue, as well as the type of knife. Differences may also be due to the way in which the tissues were prepared and stored prior to testing.

CONCLUSION

Assuming that pork ribs without skin represent an adequate surrogate for the human chest, our results indicate that a force as low as 5 N, applied to a ceremonial sword, can cause penetration. A force of approximately 11 N would represent 50% probability for a ceremonial sword to penetrate the tissues of the human chest and that force greater than 30 N represents almost 100% probability of penetration. However, with a thick skin layer, the minimum penetration force increased to 39 N and the force required for a 50% probability of penetration increased to 49 N. Although this is still a relatively low force, it likely overestimates the force necessary for the ceremonial sword to penetrate the human chest, given that the porcine skin was not held in tension, allowing it to go slack as a force was applied by the tip of the sword. In addition, we found that the penetration force did not vary significantly over a three-fold range of penetration speed.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

No humans were used for studies that are basis of this research.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data and supportive information is available within the article.

FUNDING

The research was funded by GTD Scientific, Inc.

CONFLICT OF INTEREST

The authors declare no conflict of interest financial or otherwise.

ACKNOWLEDGEMENTS

Declared none.

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