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Towards a predictive assessment of stab-penetration forces

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Abstract

Collaborative research between the disciplines of Forensic Pathology and Biomechanics was undertaken to investigate the hyperelastic properties of human skin, to determine the force required for sharp instrument penetration of skin and to develop a finite element model which reflects the mechanisms of sharp instrument penetration. These studies have led to the development of a 'stab metric', based on simulations, to describe the force magnitudes in stabbing incidents. Such a metric should, in time, replace the crudely quantitative descriptors of stabbing forces currently used by forensic pathologists.

Keywords: stabbing, sharp force injury, forensic biomechanics, impact

1. Introduction

Stabbing is the commonest mode of homicide in Ireland and the United Kingdom[1] and although proportionately less common than shootings, stabbings in the United States still account for 13.3% of homicides.[2] Furthermore, many instances of non-fatal stabbings occur, many of which go unreported to the authorities. Hitherto, forensic pathologists have responded to questions regarding the degree of force required to inflict stab wounds with expressions such as mild, moderate, considerable and severe. Such responses can be interpreted by the courts to infer the harmful intent of an assailant and also to assess the feasibility of 'run-on' scenarios.

While the problem described here is unique to forensic pathology, it is clear that it could ben-

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efit from an inter-disciplinary 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.[3] In an attempt to provide scientific quantitative assessments of the scale of force involved in stabbing incidents, we have undertaken collaborative pathological and biomechanics research. This has allowed the hyperelastic properties of human skin to be characterized, providing a new in-vitro data set to researchers. The microstructural organization of collagen fibers in the dermis has been studied allowing for the development of an anisotropic model of human skin. Experiments have been performed to determine the force required for sharp instrument penetration of human skin or skin substitutes at both quasi-static and dynamic speeds. From these studies, it has been possible to develop a finite element model reflecting the mechanisms of sharp instrument penetration of skin and also of a stab metric (equation) to calculate force magnitudes in stabbing incidents.

Finite element analysis (FEA), originally developed in the 1940s as a tool for civil and aeronautical engineering, has become an invaluable tool in biomechanics over the last three decades.[4] In essence, this is a method for subdividing a complicated mathematical problem into a finite number of small component parts, or elements, which can be solved in relation to each other. 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, and replace the need for complicated experiments.

2. Materials and methods

Skin is the soft tissue which provides the most resistance to puncture, and therefore the mechanical properties of skin are of the utmost importance in this study. A series of in vitro uniaxial tensile tests and a histological investigation were performed to characterize the mechanical behavior of human skin.[5] An algorithm was developed in MATLAB to automatically identify the orientation of collagen fibers in the dermis. This data provided sufficient information for the anisotropic modeling of human skin using the Gasser-Holzapfel-Ogden hyperelastic model.[6]

A series of experiments was performed 1) to measure the force required for a blade to penetrate skin at various 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[7, 8] and 2) using different 'sharp' implements.[9] The set-up consists of a biaxial tension device, a blade holder (shown in Fig. 1) and the test machine which controls the speed of the descending blade onto skin.

Using the experimental results of both tensile tests and stab-penetration tests, a finite element model was developed which could replicate the stab-penetration experiments using ABAQUS (a non-linear FEA commercial package). 8000 C3D8R elements have been used to simulate the process. The failure mechanism employed is one of element deletion and is shown in Fig.2. 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. In Fig.2(a), the blade has deformed the skin but no initial penetration has occurred, corresponding to the early portion of the stab-penetration experiment. Once the threshold value of the failure criterion is reached in each element, those elements are deleted and the blade progresses through the skin until full perforation of the skin occurs in Fig.2(b). The force required to fully perforate the skin is known as the penetration force.

[11] claimed that the 'sharpness' of the blade is by far the most important factor to consider with respect to penetration force. There is no doubt that the sharpness of the blade plays a major role in the level of penetration force during a stab incident, and yet, no author has quantified the effect of blade sharpness during a stabbing incident, although this has been done for cutting.[12, 13] While this is a difficult task experimentally, as controlled variation of blade tip geometry is almost impossible, numerically, it is quite possible to achieve. Using the finite element model which has been verified and validated in,[14] the characteristic dimensions of the 'carving' knife, shown in Fig. 3, have been varied systematically.

3. Results

Fig. 4 displays the variation in penetration force while isolating each of the characteristic blade dimensions. All three characteristic dimensions have an almost linear relationship with the penetration force within the range examined here. It can be seen that the tip angle is the most important characteristic dimension, having the largest variation in penetration force over the chosen range. Since the tip angle and the tip radius are the regions which make first contact with the skin, we expect these two dimensions to be dominant. The tip radius however is small, measuring between 100-500 μm and once the blade indents beyond that distance, it is the tip angle which becomes the dominant dimension.

3.1. Development of stab metric

The results of stab-penetration simulations are now incorporated into a 'stab metric' which aims to predict the minimum penetration force for a given blade. Multiple linear regression (MLR) techniques are used to fit the data to a statistical model. MLR attempts to model the relationship between two or more independent variables, e.g. tip radius etc., and a dependent variable e.g. force. It is assumed that the relationship between the independent variables and the dependent variable is linear and that the resulting residuals are normally distributed about the mean. The model is given by the equation

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \tag{1}$$

where Y is the dependent variable, X_1, X_2 and X_3 are the three independent variables, blade tip radius, blade tip angle and cutting angle respectively, and $\beta_0, \beta_1, \beta_2$ and β_3 are coefficients.[15] A total of 30 different simulations with varying blade dimensions were modeled. The fitting procedure was performed using the data analysis package available in Microsoft Excel. The evaluated regression coefficients are given in Table 1 with the 95% confidence intervals and P values. The evaluated model is given by the equation

$$\textit{Penetration Force} = -15.45 + 0.016TR + 0.69TA + 0.16CA \tag{2}$$

where TR is the blade tip radius in μm, TA is the blade tip angle in degrees and CA is the cutting angle in degrees. The penetration force has dimensions of Newtons in this form of the equation. The model was found to have an R^2 value of 97.2% which illustrates a good predictive capability of the model. A multiway ANOVA was performed on the data revealing that each of the characteristic dimensions had a statistically significant effect (i.e. $P<0.05$).

Table 1: Evaluated regression coefficients using stab metric.

Coefficient	Value	Lower 95%	Upper 95%	P-value
β_0	-15.45	-20.42	-10.48	<0.001
β_1	0.016	0.0077	0.025	<0.001
β_2	0.69	0.56	0.81	<0.001
β_3	0.16	0.026	0.29	0.026

Fig.5 compares the stab metric prediction of penetration force for a carving knife to the corresponding experimental data. It can be seen that the results of the stab metric compare favorably to the experimental data, lying within the bounds of the experimental standard deviation.

4. Discussion

A number of simplifying assumptions have been made in the development of this stab metric which should be noted. The first is 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 velocity-dependent nature of skin which sees skin behaving in a more stiff manner at higher velocities. The second simplification is that the presence of clothing has been ignored. Previous research carried out by the authors has revealed that the presence of clothing has a significant effect on the penetration force, with a single layer of denim increasing the penetration force by 50%.[9] Future work should aim to include this effect in the stab-metric. A final simplification of the model is the representation of the flesh as skin alone. This is justified by the fact that skin offers the largest resistance to puncture until cartilage or bone is met.[11] The model could be extended in the future to include underlying bone and cartilage which would enable the model to simulate the scenario where the blade has ruptured the skin and penetrated far enough to damage underlying bone (which is the case for 53% of stabbing cases[16]). Furthermore, combining these two models could have applications in other injuries, such as lacerations, where the skin is generally crushed between a blunt object and underlying bone.

A finite element model of human skin has been developed which can accurately simulate a stabbing incident. This model has been used to quantify the influence of blade geometry on the penetration force. It has been shown that the three characteristic dimensions possess an almost linear relationship with the penetration force over the range investigated. The blade tip angle was found to be the most important dimension in establishing the penetration force of a given blade. Once the blade dimensions are known, the statistical stab metric developed here can be used to predict the minimum force required to penetrate bare human skin using a given blade. While the stab metric described here cannot yet be used for medico-legal purposes, it is hoped that even in its current form, it may prove to be a useful tool in forensic pathology by offering a quantitative assessment of a given blade.

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Figures

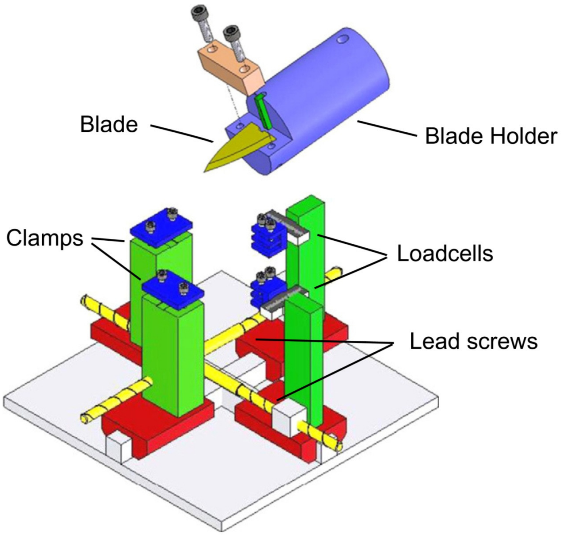


Figure 1: Illustration of biaxial device.[10]

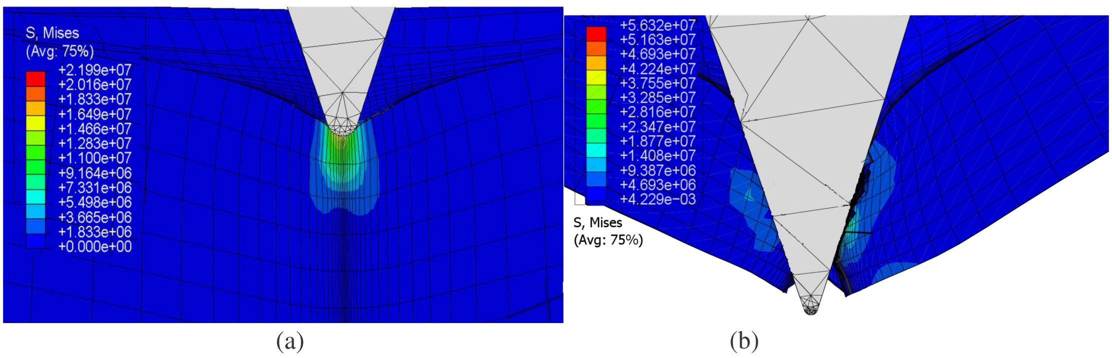


Figure 2: Numerical progression of a carving knife through human skin (units in Pa).

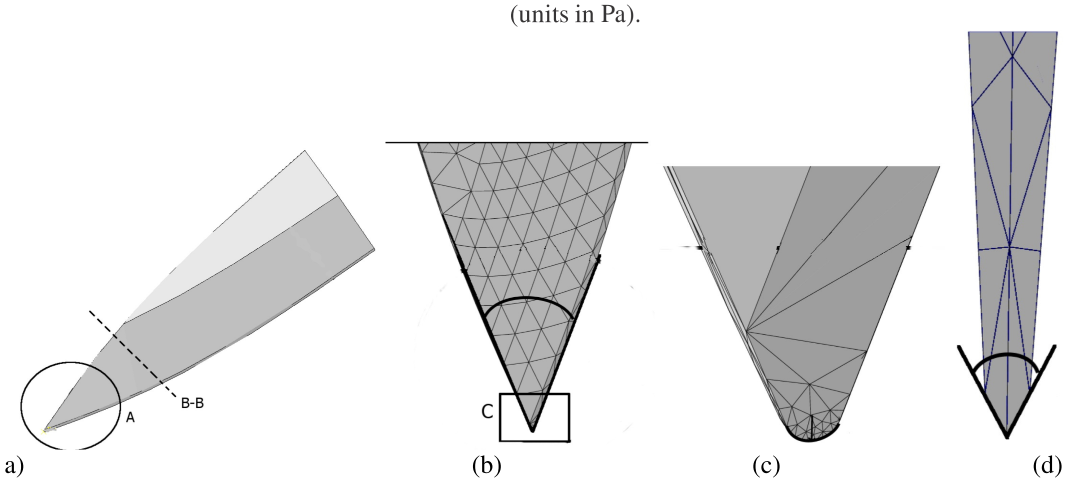
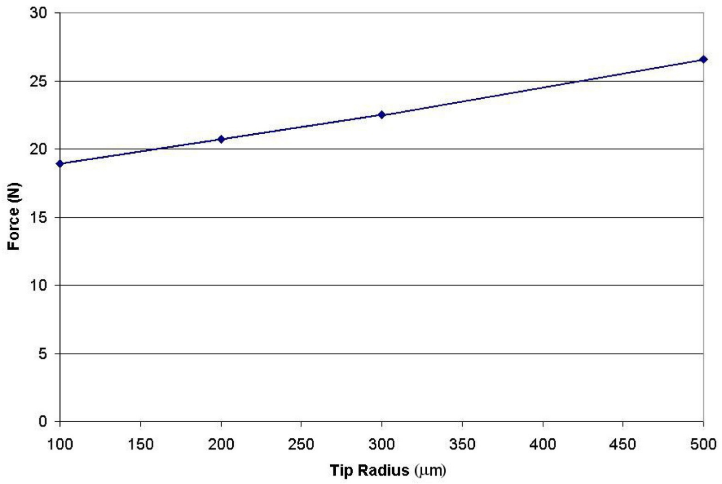
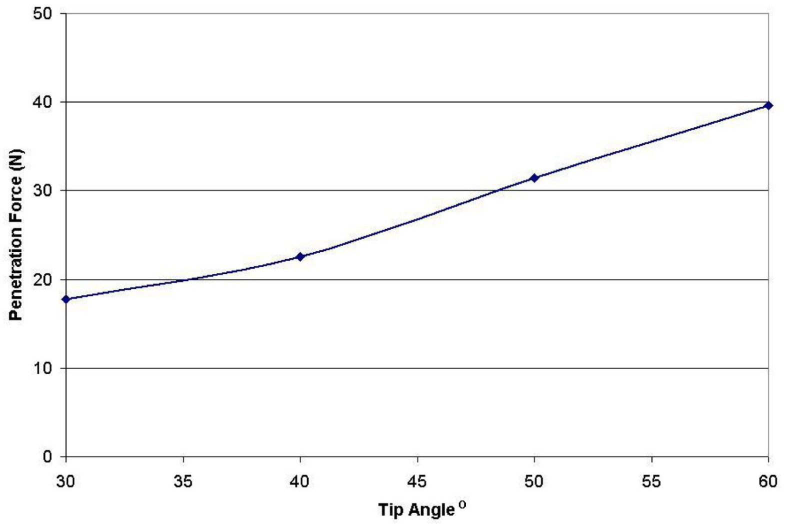


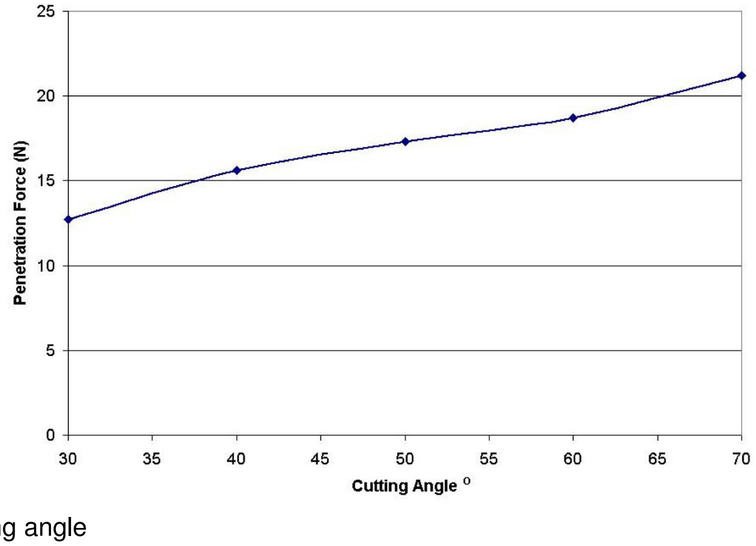
Figure 3: Indicative blade dimensions (a) blade (b) Tip angle (zoom at A) (c) Tip radius (zoom at C) (d) cutting angle (cross section B-B)



(a) Blade tip radius



(b)Blade tip angle



(c) Cutting angle

Figure 4: The maximum penetration force as a function of the characteristic blade dimensions.

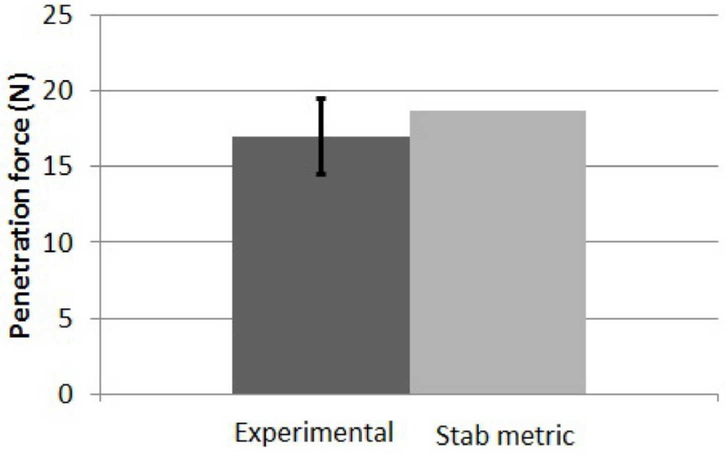


Figure 5: Comparison of experimental data for carving knife penetrating human skin at quasi-static speeds to the same stab-metric prediction.