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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.

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 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/m^3 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.

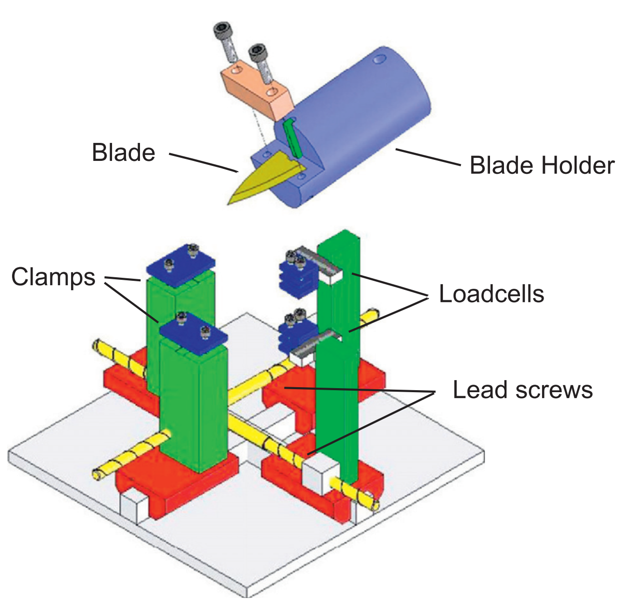

Fig. 1. Illustration of biaxial device.

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].