A Simplified Model to Determine the Contribution of Strain Energy in the Failure Process of Thin Biological Membranes during Cutting

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ABSTRACT: Thin biological membranes such as skin are highly deformable, nonlinear in behaviour and fracture resistant. As a result of these properties, measuring the resistance to fracture of such materials is difficult. This paper investigates the resistance to fracture of a thin biological membrane, using the example of animal skin. Models of cutting using a fracture approach are examined and a review of the structure and mechanical properties of skin is given. A review of previous work in examining the fracture behaviour of skin is carried out and a strain energy-based failure model for skin is proposed. A method of measuring the fracture resistance of skin in opening mode (mode I) using this failure model is described. Values for the resistance to fracture of skin samples were calculated from experiments to be 2.32 ± 0.40 kJ m^{-2}. These results were found to be in good agreement with the literature. The model and experimental technique proposed here may be applied to establish the failure properties of membranes and, in particular, a range of soft tissues under a variety of cutting conditions.

KEY WORDS: *biological membrane, cutting, fracture toughness, sharpness, skin*

NOTATION

X	Force acting on the blade
u	Displacement of the blade
$d\Lambda$	Strain energy stored in the sample due to it being deformed by the blade
J	Resistance to fracture
dU	Strain energy stored in the sample due to it being under tension
$d\Gamma$	Energy lost in remote plastic flow because of the force of blade acting on the sample
dA	Area of cut surface created
E	Young's modulus
ε_0	Zero-strain offset value

Introduction

Biological membranes, such as skin and sub-intestinal mucosa, are highly deformable. Typically, they are stressed at levels far below those of engineering materials; however, they may be strained, by orders of magnitudes, more. This can mean that the strain energy stored in the skin of the cheek when yawning is similar to that in mild steel at ordinary engineering stresses. Most animal soft tissues are, fortunately, very resistant to fracture and do not tear catastrophically, or burst like a balloon, when they are damaged by piercing or cutting [1].

Skin is a composite material the primary constituent of which, apart from water, is primarily collagen fibres [2]. Its morphological structure is best described as an alignable collagen network intermeshed with an elastin network in a ground substance of proteoglycans. Skin is a viscoelastic, anisotropic material with nonlinear stress–strain behaviour and its stress–strain curve is best described as being J-shaped. The stress–strain curve is divided into two regions – a low stiffness region where the properties are determined by the elastin network and a higher stiffness region where the properties are determined by the collagen network. If a load is applied to a sample of skin and the load then released, some of the energy that was stored will be lost. According to Silver *et al.* [3], energy that is applied to the skin is partially dissipated

through viscous sliding of the collagen fibrils during alignment of the fibres with the direction of the force. This may give rise to stress relaxation and creep effects [4] over longer loading periods.

As a result of its physical nature, it is difficult to conduct precise experimental testing of skin. Skin is not easily cut when excised and its low stiffness implies that it will deform under its own weight, causing errors in zero-strain measurement. Its mechanical properties depend on various other factors such as age, excision location, moisture content and loading history [5].

One of the medical applications that may benefit from this research is the process of cutting soft tissue. Tissue cutting is obviously important from a medical perspective with many different designs of scalpel blades, scissors and punch cutters available. Izmailov *et al.* [6] reported that wounds produced by sharper blades heal better and more quickly. There is little understanding of the 'cuttability' of various biological tissues in surgical practice – i.e. the nature of the relationship between the blade and the quality of cut achieved. From a wider engineering perspective, little is known about the performance of blade-type cutting instruments and the true meaning of terms such as 'sharp' and 'blunt' in the context of blade performance.

For biological and biomaterials, much work has been performed on the fracture of hard tissues such as bone and bone cements, but little work has been carried out on the failure of soft biological tissues such as skin. Fracture analyses have been used by some researchers to model the cutting failure of thin membranes. Rivlin and Thomas [7] studied the fracture of rubber sheets and measured the resistance-to-tear, in an opening mode, of these sheets in terms of energy. The 'tearing energy' they calculated was effectively a measure of the resistance to fracture. Purslow [8] carried out tests on biological membranes, fracturing them in a tearing mode and used the results of these tests to calculate the critical strain energy release rate, or resistance to fracture. Lake and Yeoh [9] carried out work similar to that of Rivlin and Thomas [7], but forced the crack to progress by using a razor blade instead of simply tearing the material apart. The result of much of this work is strongly influenced by the method of application of energy to the crack tip. Forces are applied to the crack tip by pulling apart 'legs' of the specimens (Figure 1A). Substantial strain energy that contributes to the fracture of the specimen is stored in these legs.

Pereira *et al.* [10] noted that biological tissues have a high apparent resistance to fracture. This was attributed to a phenomenon known as crack blunting, where the viscoelastic nature of biological tissue

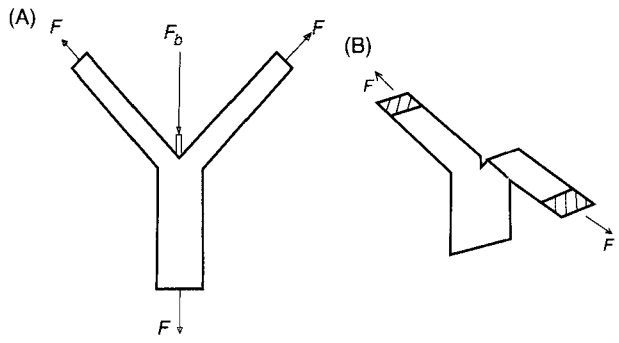

Figure 1: (A) Configuration of fracture test by Lake and Yeoh [9]; (B) configuration of fracture test by Purslow [8]

allows it to flow at the tip of the crack, blunting it and therefore requiring a much higher level of force to progress the crack further. The high levels of force that then need to be applied to the material cause creep and plastic flow, resulting in hysteresis. Consequently, much of the energy stored in the material does not go into crack production. The experimental method of Pereira *et al.* [10] (where the tissue is cut using a scissors) ensures that all energy input into the test goes into crack production, allowing a more accurate measure of the resistance to fracture of the material.

The tear tests carried out by Purslow [8] fractured specimens of sea anemone and rat skin using the configuration shown in Figure 1B. The samples were mounted in a tensiometer and extended at 50 mm min^{-1}. The results of these tests calculated the resistance to fracture of rat skin to be 11.08–13.2 kJ m^{-2} with the crack orientation in the circumferential direction and 16.53–26.9 kJ m^{-2} in the longitudinal direction. This tear test causes mode III fracture. Periera *et al.* [10] placed samples of human and rat skin between the blades of a scissors mounted in a universal testing machine. The samples were mounted unstretched on a wire mesh, the scissors closed by moving the crosshead of the machine, and the force required to cut the skin was measured. This configuration also causes mode III fracture. The resistance to fracture calculated for human hand skin was in the range of 1.7–2.6 kJ m^{-2}. These values are an order of magnitude lower than those reported by Purslow [8], which was attributed to crack blunting [10].

A typical stress–strain curve for skin is shown in Figure 2A. It is apparent from this that any single value for the stiffness, E, of skin is only meaningful for a particular phase in the straining of skin. Not surprisingly, the published values for Young's modulus of skin vary enormously, from 0.7 to 150 MPa [2, 11–14]. It should be noted that these reported values are for different phases of the stress–strain curve and for different samples, animal species, ages of skin and test scenarios.

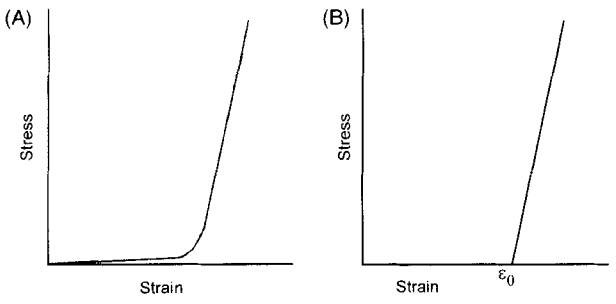

Figure 2: Stress–strain behaviour of skin as described by Daly [17]

In this study, a simplified stress–strain behaviour was assumed as shown in Figure 2B. It is assumed that until a certain level of strain, ε_0, is reached, there is no strain energy stored in the material. From this point on, the behaviour is linear elastic.

This paper investigates the resistance to fracture of a thin biological membrane. A simplified model of soft tissue fracture is presented based on the cutting of the tissue by a single sharp blade. An experimental technique is used which minimises the energy lost in remote plastic flow, ensuring that as much as possible of the energy input into the system goes directly into crack production, while at the same time testing the material in an opening mode. Viscoelastic effects are assumed to be negligible, as the application of the strain and subsequent failure occurs over a short time period. The technique also allows the material to be tested under tension, which is the normal *in vivo* condition [5].

Failure Model for Skin

Based on the energy equation for quasi-static fracture [1], it is proposed that the energy balance for the mode I fracture caused by cutting of a thin membrane using a single blade may be written as:

$$Xu + \mathrm{d}U = \mathrm{d}\Lambda + J\,\mathrm{d}A + \mathrm{d}\Gamma \qquad (1)$$

where X and u are the force acting on the blade and its displacement, respectively. The term $\mathrm{d}U$ pertains to strain energy stored in the membrane being cut. It is assumed that as the material is under tension before cutting, energy will be released from the material as it is being cut. J is the resistance to fracture.[1]

When a blade is pushed into a membrane, the cutting process does not begin immediately. The membrane may initially deform in front of the blade until eventually cutting commences. $\mathrm{d}\Lambda$ is the elastic strain energy stored in the membrane during this deformation. This strain energy can be recovered at the end of the cutting process if the deformation is elastic. $J\,\mathrm{d}A$ is the work absorbed by the membrane in creating the new crack surfaces, and $\mathrm{d}\Gamma$ is work absorbed in remote plastic flow. Equation 1 may be rearranged to give resistance to fracture:

$$J = \frac{(Xu - \mathrm{d}\Lambda) + \mathrm{d}U - \mathrm{d}\Gamma}{\mathrm{d}A}. \qquad (2)$$

To help understand the meaning of Equation (2), it is useful to compare the force–deflection graphs for a standard crack test in opening mode (mode I) and for a cutting test, also in mode I (Figure 3).

Consider a solid containing a crack of initial size a_1 that is propagated to length a_2 under a constant load [1]. The applied force is X (loaded perpendicular to the crack) and u is the displacement of the applied force. The load is applied and increased until the crack starts to propagate (OB; Figure 3A). The crack propagates at a controlled rate along BC and has increased in length from a_1 to a_2. As the load is

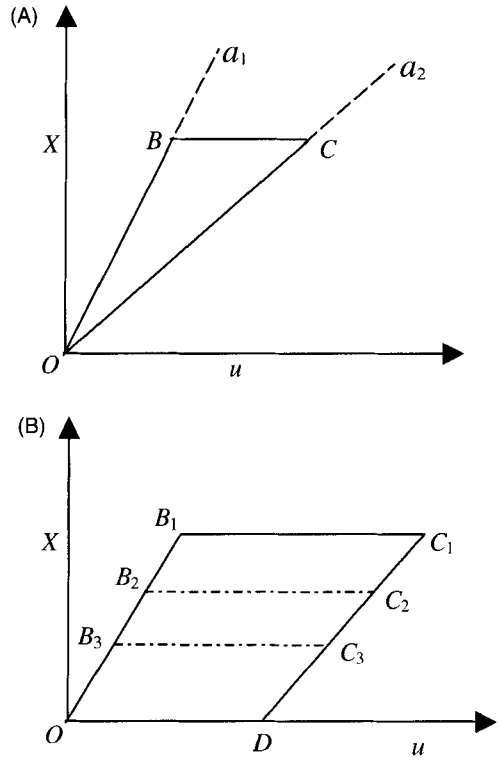

Figure 3: (A) A load–deflection graph for a cracked solid loaded perpendicular to the crack for an indealised quasi-static fracture; (B) a load–deflection graph for a blade cutting a pre-strained material showing different failure paths, i.e. OB_1C_1D, OB_2C_2D and OB_3C_3D

[1] Note that Atkins & Mai [1] refer to J as the fracture toughness. As this refers to the K_{Ic} value to most engineers, in this paper, J will be referred to as the resistance to fracture.

released, the body relaxes along path *CO*. The energy required to cause the fracture (effectively the resistance to fracture) is the area *OBC*. Note that path *OC* has a different slope than *OB* as the compliance of the body has been increased.

Now consider a membrane being cut with a blade (e.g. Lake and Yeoh [9]). Note that in this case, X is the force applied to the blade and u is the displacement of the blade. As the blade is loaded along path *OB* (Figure 3B), the membrane in front of the blade is strained, eventually fracturing (path *BC*). After increasing the length of the crack by cutting, the force on the blade is released along path *CD*, releasing whatever strain energy was stored in front of the blade.

The loading path does not return to the origin and the slope of path *OB* will differ from that of path *CD* as the compliance of the membrane sample being cut will have changed. In this case, the energy required to cause the fracture is the area *OBCD* plus any strain energy released by the membrane itself [i.e. the dU term in Equation (1)]. There are different possible paths shown in Figure 3B, and which of these is followed during fracture will depend on both the level of strain energy pre-existing in the membrane and the sharpness of the blade driving the cut. The more strain the membrane is under before cutting (i.e. stretching the skin), the less energy (force) will have to be input by the blade to cut the membrane.

For any membrane, Equation (2) can be used to calculate the resistance to fracture, J. The (Xu – dΛ) term can be found by calculating the area under the graph. The dU term can be calculated for an elastic membrane if the initial strain of the membrane and its Young's modulus is known. For a nonlinearly elastic membrane such as skin, a stress–strain curve would be required to calculate dU. Finally, if the fracture process is being caused by a sharp blade, the level of remote plastic flow covered by the dΓ term should be reduced to such a level so that it can be regarded to be negligible.

Equipment

A special rig was designed to carry out the cutting tests. An initial prototype rig was built and some tests carried out with this to finalise the design for the final rig (shown in Figure 4).

This rig is composed of two primary modules. The first module is a DC motor-driven blade holder that allows the blade to moved linearly. The position of the blade is measured using a linear potentiometer (Pioden Model PD20, Pioden Controls, Canterbury, UK). The blade can be clamped at a variety of angles

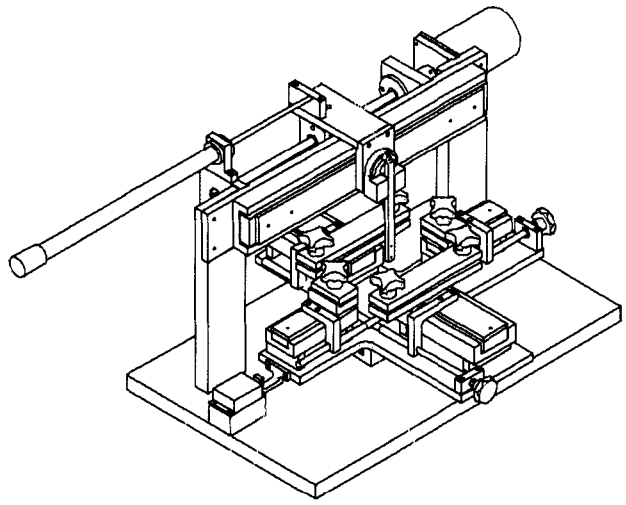

Figure 4: The test rig used

in this holder. The second module is a clamp designed to hold skin samples. This allows skin samples to be clamped in both uniaxial and biaxial tension. The biaxial clamp is mounted on a linear guide and fixed to the frame of the machine with a low capacity load cell (*c.* 20 N; Pioden Model UF1). This design allows skin samples to be cut using a scalpel blade while measuring the cutting force and the distance travelled. The rig is connected to a standard PC with a data-acquisition device installed (National Instruments 6014, National Instruments (UK) Ltd, Newbury, UK). The PC collects the data and controls the rig movement. This rig can measure forces to an accuracy of *c.* ±0.05 N and position to a resolution of 0.08 mm. A benchtop tensile tester (Hounsfield H10K-W, Tinius Olsen Ltd, Salford, UK) was also used to carry out tensile tests on skin samples so that a value for Young's modulus could be estimated.

Method

For these experiments, chicken skin was used. Partially deboned fresh chicken breasts were purchased with the skin intact. The skin was removed from the muscle tissue by a combination of gentle pulling and excising. The skin membrane was examined to ensure that it was intact after removal. Any fat adhering to the inside surface of the skin was removed by scraping with a sharp knife. The samples were cut to a suitable size for either tensile testing or cutting and wrapped in aluminium foil (to prevent the samples from drying out). They were then placed in an icebox for transportation to the test rig. Both tensile and cutting tests were carried out parallel to the long axis of the chicken breast, which corresponds to the head–tail axis of the animal. All tests were carried out at room temperature.

A series of tensile tests were carried out to establish the stress–strain behaviour of the skin. Six samples were tested to destruction on the benchtop tensile tester. Values for ε_0 and E were then calculated. Cutting tests were carried out on nine samples. The procedure for each sample was as follows. The sample, which was cut to a suitable size (*c.* 120 × 40 mm) was removed from the icebox and allowed to reach room temperature. The sample was removed from its foil wrapping and its thickness measured at a number of points using a special device designed to measure the thickness of leather samples (manufactured by Pet. Arn. Altena, Ramscheid, Germany). This device functions like a micrometer but exerts low pressure on the skin. The sample was placed between the clamps and its unstretched width measured with a vernier. A strain of 25% was applied to the sample and the stretched width measured. The blade, angled at 60° to the skin surface, was advanced in from the left-hand free edge of the sample producing an initial cut. It was then stopped and reversed until it was not in contact with the specimen. This was to ensure that the blade was aligned with the intended cut. The blade was then advanced through the sample at 0.02 m s^{-1} with the distance travelled and the force to cut being recorded. After cutting through the sample for *c.* 60 mm, the blade was stopped and then reversed until it was no longer in contact with the specimen. This procedure was repeated for all the samples. The blade was cleaned with alcohol between tests to remove any residue from the blade. This was to avoid frictional effects caused by adhering residue (Huebscher *et al.* [15]).

Results

From the tensile tests, the average value of ε_0 was calculated to be 0.131 ± 0.031 and an average value for E was found to be 1.28 ± 0.24 MPa (using engineering stress–strain). The value of J [Equation (2)] was then calculated. The (Xu – dΛ) term was found using a simple numerical integration method, effectively finding the area under the curve. A typical Xu graph for one of the tests is shown in Figure 5.

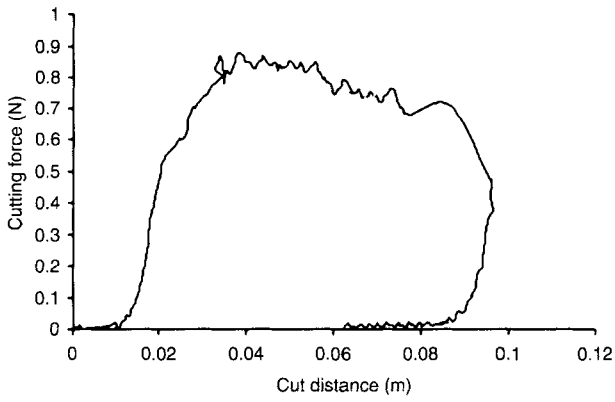

Figure 5: Results from cutting one of the samples (sample 10)

The value of dU was found by assuming that $U = \frac{1}{2}E\varepsilon^2$, where ε equals the actual strain applied to a sample minus ε_0. It was assumed that where the material has been cut, all the stored strain energy in that segment of the sample has been released into the fracture/cut. This is the approach taken by Rivlin and Thomas [7]. As sharp blades were used in the experiments, it was assumed that dΓ was negligible. Finally, dA was calculated as the product of the distance cut and the average material thickness. Table 1 presents the resistance to fracture calculated from testing the first eight samples. The average resistance to fracture measured was 2323 J m^{-2} with a standard deviation of 399 J m^{-2} using engineering stress/strain. The contribution of the strain energy released to the resistance to fracture value was small in this experiment, an average of 7%. An additional sample was tested using a blade that had been deliberately blunted (the edge was gently dragged three times across the finishing side of a hone). In this case, the force required to cut the sample

Table 1: The resistance to fracture for the first eight samples using engineering stress/strain

Sample	Area under force–distance curve (J) (Xu – dΛ)	Strain energy released to crack (J) (dU)	Total energy used (J) [(Xu – dΛ) + dU)	Crack area (m^2) [dA]	Fracture Toughness (J m^{-2}) (J)	% supplied by strain energy
1	0.0471	0.0051	0.0522	2.29E–05	2279.82	10.8
2	0.0725	0.0069	0.0794	3.73E–05	2125.91	9.5
3	0.0711	0.0022	0.0734	2.72E–05	2700.49	3.1
4	0.0551	0.0067	0.0617	3.37E–05	1832.67	12.1
5	0.0643	0.0040	0.0683	2.21E–05	3089.55	6.3
6	0.0586	0.0022	0.0608	2.95E–05	2060.99	3.8
7	0.0620	0.0037	0.0658	2.80E–05	2350.53	6.0
8	0.0493	0.0025	0.0517	2.41E–05	2146.20	5.0

The average value was 2323 ± 399 (±SD). The value of E used was 1.28 MPa.

increased from *c.* 1 to 3.5 N. The average resistance to fracture value calculated in this case was 7658 J m^{-2}.

Discussion

The results of the tests described in this paper and given in Table 1 compare favourably with those in the literature (Pereira *et al.* [10]; shown in Table 2). There is substantial variation in these results, both in the average value and the deviation. This can be explained by the fact that the measurements are for different animal membranes at different ages. For example, the human samples used by Periera *et al.* [10] were from 70-year-old cadavers and the rat skin samples from adult rats (presumably much younger). These are the only published results for resistance to fracture in opening mode (mode I). The significance of this finding is for the development of a relatively simple and repeatable model to determine realistic failure properties of soft tissues during the cutting process. Such a model may be used to evaluate different cutting instruments.

The accuracy of the results needs to be considered, with some awareness of the methods employed and the material being tested. In the calculation of resistance to fracture carried out here it was assumed that there was no remote plastic flow, i.e. $d\Gamma$ term in Equation (1) is assumed to be zero. This is regarded as a reasonable assumption as the force exerted by the blade on the skin when cutting is quite low (*c.* 1 N). This force will not significantly plastically deform the skin in regions remote from the cut tip.

In calculating the strain energy stored in the sample, a simplified model of the stress–strain behaviour was assumed as described. Given that the strain energy makes a small contribution to the overall fracture toughness (on average, 7%), this is seen to be reasonable. Moreover, note that in this experiment the E value was only calculated using engineering stress/strain and not true stress/strain (Groover [16]). Using true stress–strain would increase the value of E found (1.28 MPa) and consequently the resistance to fracture. It is not clear from the literature which values should be used. Finally, the value of E measured is lower than values quoted in the literature, the lowest value quoted by Vogel [11] is 12.5 MPa. However, this value is for human, not chicken skin and Vogel notes that younger skin (such as that from chickens bred for food use) typically has lower E value. Further study of the material properties of chicken skin is required to ensure that the contribution of the released strain energy is accurately known.

To calculate the strain energy that is released from the material as it is being cut, it has been assumed that where the material has been cut, all the stored strain energy in that segment of the sample has been released into the fracture/cut. This is similar to the approach taken by Rivlin and Thomas [7], where they used a 'pure shear' testpiece, similar to the configuration used here. In their case the sample was cut from the edge and they divided the sample into four zones. Zone A is the material directly above and below the cut (i.e. along the cut edges) – this area is unstressed. Zone C is around the tip of the cut and is stressed in a complex way. Zone B is sufficiently far from the cut tip to have its stress field unaffected by the cut and zone D is at the far end of the sample from the cut, but its stress field is affected by the fact it is at the edge of the specimen. Cutting the specimen causes zone A to grow at the expense of zone B, but C and D remain the same, i.e. increasing the cut by a certain distance, releases the strain energy from a section of the sample of the same length.

Skin can also exhibit significant creep [17] when loaded for long periods of time. For this reason, samples were cut as soon as possible (within 1 min) after mounting. It may be possible to incorporate the effects of creep by designing a clamping system that can continuously measure the tension and therefore the strain energy in the material being clamped.

A single sample was cut with a blunted blade to investigate the effect of blade sharpness on the results. As expected, a substantial increase in cutting force was recorded and hence the resistance to fracture value increased. This indicates that the experimental method will be useful for evaluating different blade design and material combinations.

Table 2: Comparison of values for fracture toughness (resistance to fracture) reported by Pereira [10] with those calculated in this study

Tissue	Source	Resistance to fracture (J m^{-2})
Chicken skin (along the head–tail axis)		
Using engineering stress/strain	This experiment	2323 ± 399
Dorsal skin (human hand)		
Longitudinal	Periera *et al.* [10]	1777 ± 376
Circumferential	Periera *et al.* [10]	1719 ± 674
Palmar skin (human hand)		
Along skin creases	Periera *et al.* [10]	2365 ± 234
Across skin creases	Periera *et al.* [10]	2616 ± 395
Abdominal skin of adult rats		
Random direction	Periera *et al.* [10]	588 ± 152

The objective of the experiments carried out here was to establish if the method of cutting used was capable of measuring the resistance to fracture of thin biological membranes, in this case skin. The resistance to fracture values measured are in agreement with those published in the literature, indicating that the method is successful. The results of this work will be used to develop models of the relationship between blade sharpness and the quality of the cutting of soft tissue in surgical procedures. Immediate future work will focus on improving the accuracy of these results.

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