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The fracture properties and mechanical design of human fingernails

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Summary

Fingernails are a characteristic feature of primates, and are composed of three layers of the fibrous composite keratin. This study examined the structure and fracture properties of human fingernails to determine how they resist bending forces while preventing fractures running longitudinally into the nail bed. Nail clippings were first torn manually to examine the preferred crack direction. Next, scissor cutting tests were carried out to compare the fracture toughness of central and outer areas in both the transverse and longitudinal direction. The fracture toughness of each of the three isolated layers was also measured in this way to determine their relative contributions to the toughness. Finally, the structure was examined by carrying out scanning electron microscopy of free fracture surfaces and polarized light microscopy of nail sections.

When nails were torn, cracks were always diverted transversely, parallel to the free edge of the nail. Cutting tests showed that this occurred because the energy to cut nails transversely, at approximately 3 kJ m^{-2}, was about half that needed (approx. 6 kJ m^{-2}) to cut them longitudinally. This anisotropy was imparted by the thick intermediate layer, which comprises long, narrow cells that are oriented transversely; the energy needed to cut this layer transversely was only a quarter of that needed to cut it longitudinally. In contrast the tile-like cells in the thinner dorsal and ventral layers showed isotropic behaviour. They probably act to increase the nail's bending strength, and as they wrap around the edge of the nail, they also help prevent cracks from forming. These results cast light on the mechanical behaviour and care of fingernails.

Key words: fingernails, mechanics, fracture.

Introduction

One of the characteristic features of primates is their possession of fingernails and toenails (Le Gros Clark, 1936). These are homologous to the claws of most other mammals, but unlike claws, nails are flattened, almost straight in their longitudinal axis and cambered transversely. The evolution of the nail seems to have been associated with changes in the locomotor habits of primates away from movement along the large diameter trunks and branches on which claws provide excellent grip, to locomotion along smaller diameter branches and twigs (Cartmill, 1974; Hamrick, 1998). Grip on such supports was improved by the development of broad apical pads and epidermal ridging (fingerprints). The change from claw to nail probably occurred at the same time.

The structure of human nails has been quite well studied, both by primatologists (Le Gros Clark, 1936; Soligo and Muller, 1998) and by clinicians (Lewis, 1954; Lewin, 1965; Achten, 1981; Dykyj, 1989; Ditre and Howe, 1992). The nail (Fig. 1A,B) is composed of three layers of keratinous tissue, which are laid down by the matrix at the base and below the nail (Fig. 1C). The narrow dorsal layer, which is composed of moderately hard keratin, is laid down along the roof and at the very base of the nail bed, though it is also laid down along the lateral fold. The harder intermediate layer is laid down along the proximal nail bed up to the end of the lunula, while the narrow ventral layer is made of soft keratin, and is laid down towards the middle of the nail bed. Towards the tip of the nail bed the protective hyponychium, which seals off the gap between the nail and finger, is produced. The cells of the nail are produced continuously and become keratinised, compacted and cemented together, before being forced down the nail bed; the transition to mature tissue in the main intermediate layer occurs at the end of the white lunula or 'half moon'. The growth rate is approximately 1 mm per week.

Despite our extensive knowledge of the structure and development of nails, little attempt has been made to relate their structure to their mechanical function. It is generally agreed that nails serve as a stiff backing to the soft terminal pads, preventing the skin at the ends of the finger and toes from rolling backwards over the distal phalanx. They thereby help to improve grip, sensitivity and manipulation of small objects. In addition, of course, the nails can be used mechanically themselves: to prise open cracks, lever up objects, and scratch and fight. During all of these activities, nails are loaded from below and have to resist upward bending forces. In two ways they are clearly well suited to doing this. First, they are convex in shape like the channel veins of insects (Wootton, 1981), feather shafts (Purslow and Vincent, 1974), and petioles of many plants (Vogel, 1988; Ennos et al., 2000). Second, nail, like hair, horn and hoof, is composed of a composite material, keratin, in which long, slender α-keratin protein fibres are embedded in an amorphous protein matrix (Fraser and MacRae, 1980), an arrangement which should make it both stiff and tough. The properties of the nail, however, particularly its fracture properties, will depend on the shapes of the cells of which it is composed and the orientation of the keratin fibres within them. Unfortunately, though previous authors state that the cells are flattened in the plane of the nail (Achten, 1981), they give little information about the shape of the cells or orientation of keratin within that plane. Baden (1970) deduced from x-ray diffraction that the keratin fibres are preferentially oriented transversely across the nail, but as he failed to distinguish between the three layers, it was impossible to say whether or not this occurs throughout the nail's thickness.

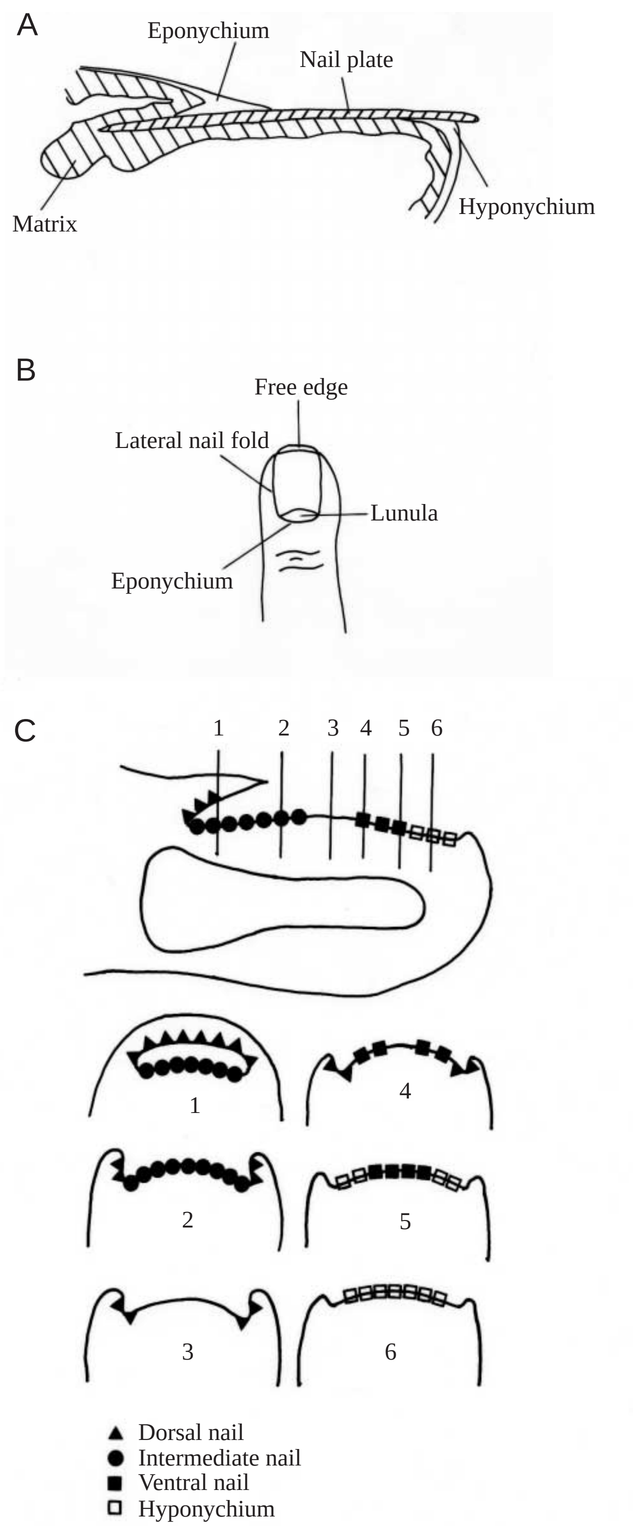

Fig. 1. Longitudinal section (A) and top view (B) of the human fingernail, showing its gross structure and relation to the surrounding structures, and (C) schematic longitudinal and transverse sections through the human finger, showing the sites of nail generation. After Lewis (1954).

From a mechanical viewpoint, the two obvious ways of orienting the fibres in the nail both have advantages and disadvantages. The optimal way to produce a nail that would resist upward bending would be for the cells and fibres to be orientated longitudinally. This has the disadvantage, however, that such a nail would also readily split longitudinally along its length, damaging the delicate nail bed. An optimal design for preventing damage to the nail bed would be to orientate the cells and fibres transversely, parallel to the edge of the lunula in the manner deduced by Baden (1970). Any cracks would therefore tend to run across the nail. Such an orientation of fibres parallel to the edge of the generative tissue is indeed seen in horses' hooves (Bertram and Gosline, 1986; Kasapi and Gosline, 1997), where it helps to prevent cracks running up the hoof. This arrangement works well in these thick structures, which are loaded mainly in compression. However, in narrow nails, which are regularly subjected to bending forces, cracks could readily be produced at the margins or surface of the nail, and once produced would run across it, so that the nail would readily break.

This study was designed to investigate how the composite human fingernail combines such apparently mutually exclusive properties as the ability to resist bending, to resist cracks forming, and to prevent cracks, once formed, running longitudinally down the nail. To do this, we carried out a series of mechanical tests and microscopic studies. First, we investigated how cracks run through nail material. Next we carried out scissor cutting tests to determine how the toughness of nail material varies with the orientation of the crack driven through it; we also measured the toughness of the individual layers. Finally we investigated the fine structure of nails by taking scanning electron micrographs of the fracture surfaces of nails, and of their outer surface, and carried out polarizing light microscopy to determine the preferred orientations of keratin fibres.

Materials and methods

Nail clippings

Human fingernail clippings, each approximately 3 mm deep, were cut from healthy young adult human subjects using nail scissors and were then kept fully hydrated until use by immersing them in water. 20 were used for tear tests, a further 15 for whole nail scissor cutting tests, and ten for individual layer scissor cutting tests; a final five were subjected to microscopic examination.

Tear tests

20 nails were subjected to qualitative tear tests to determine if they tore preferentially in any orientation. A 1 mm long notch was cut into each nail section with a razor blade, at either the central point of the distal edge or the side edge (Fig. 2). The two ‘legs’ of each nail were then held with tweezers and pulled in opposite directions, out of the plane of the nail, to give a shearing force that would cause the crack to propagate through the sample. The samples were then examined using a Wild M8 dissecting microscope (Heerbrugg, Switzerland) to determine the orientation of the free-running crack.

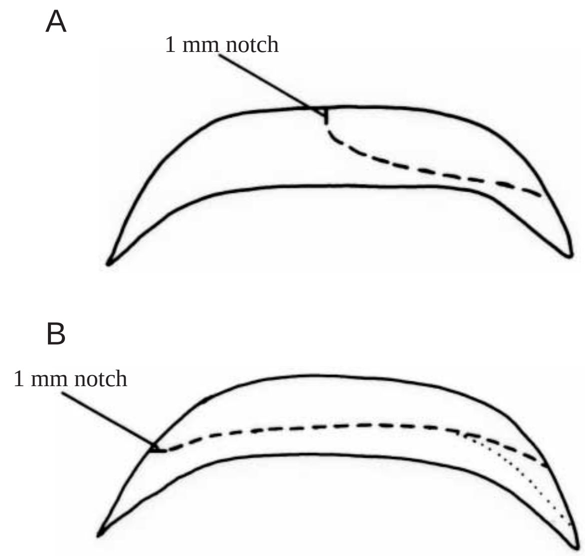

Fig. 2. Typical directions of crack propagation which occur when attempts are made to tear nails (A) in the longitudinal distal to proximal direction and (B) a transverse direction. Broken lines show failure along the entire nail. The dotted line shows how failure can occur in the dorsal layer. In A the fracture is deflected transversely.

Scissor cutting tests on whole nails

Each nail clipping was cut into four sections, giving two sections from the central region of the nail and two from the outer edges. The comparative toughness to fracture between inner and outer sections and between cuts across and down each nail was then investigated by carrying out scissor cutting tests on each section; sections from the left hand side of the nail were cut transversely, while the two from the right hand side were cut longitudinally.

The scissor cutting tests were similar to those devised by Lucas and Pereira (1990), and widely used since to investigate the toughness of leaves and other plant tissues (Wright and Illius, 1995; Choong, 1996; Lucas et al., 1997, 2000). A pair of precision scissors (Radio Spares model 539-609, Corby, UK) was mounted on the lower platform of a model 4301 universal testing machine (Instron, High Wycombe, UK), with its downward-pointing blade held rigid. The scissors were opened and the crosshead of the Instron, with a 100 N load cell mounted on it, was then lowered until a probe on the crosshead just touched the handle of the scissors. A sample of nail was then removed from the water, dried with tissue paper to remove surface water and attached, orientated in the correct way, to the lower blade of the scissors using adhesive gum.

To perform the actual tests, the crosshead of the Instron was then lowered by a distance of 5 mm at a rate of 10 mm min^{-1}, causing the blades of the scissors to close and cut through the nail. The force required to do this was measured by the load cell, and an interfaced computer calculated the total energy required by integrating the force over distance. Finally the crosshead and scissors were returned to their original positions and the procedure was repeated, but without any nail. The net energy to cut through the nail was taken to be the difference between the energy required to close the scissors with and without the nail. Finally the toughness of the nail was calculated by dividing the energy required to cut through it by the cross sectional area of the cut surface; this was equal to the length of the cut, measured using calipers, multiplied by the mean thickness of the nail, measured using a micrometer screw gauge and taking three measurements per sample.

The mean and standard deviation of the toughness in the transverse and longitudinal planes of inner and outer nail section were calculated. Paired *t*-tests were used to determine if there was any difference between the toughness in the two directions and between inner and outer regions of the nail.

Scissor cutting tests on individual layers

Samples of the three nail layers were prepared by wetting clippings for 24 h and then peeling the individual layers apart with forceps. This process produced good separation of the three layers, at least over small areas. Ten nail clippings were prepared in this way, and cut in half to give two samples of each layer either side of the centre of the nail. The samples were then subjected to scissor cutting, pieces to the left of the clipping being subjected to transverse cuts and those to the right to longitudinal cuts, and values for toughness were calculated as described above, measuring the length of cut and thickness of the sample in the same way. Paired *t*-tests were used to determine whether there was a difference in transverse and longitudinal toughness for each individual layer.

Scanning electron microscopy

Fracture surfaces of nails were prepared by the method used to carry out the tearing tests. The nails were then mounted on scanning electron microscopy (SEM) stubs, with the fracture surface upwards, coated in gold and examined under a Cambridge 360 scanning electron microscope (Cambridge, UK).

Polarized light microscopy

Preferred fibre orientation was tested using polarized light microscopy, using a method similar to that of Earland et al. (1962). Sections of each of the three layers of the nail were produced by placing lengths of nail on a microscope slide and cutting and scraping away the other layers using a razor blade. Sections were then observed between crossed Nichol prisms, and the microscope stage rotated, while the brightness of the image was examined. If the fibres have a preferential orientation the image should be bright or dark according to the orientation of the fibres with respect to the prisms, the image being brightest when the fibres are arranged at 45° to the prisms and darkest when they are parallel or perpendicular to them. If there is no preferred orientation the image will remain dark in all orientations.

Results

Tear tests

There were striking differences in the ease with which cracks could be propagated in the different directions. When we attempted to tear the nail in the longitudinal orientation towards the nail bed, the force required seemed to be large and cracks never ran longitudinally. In all ten nails the crack deviated, running obliquely through the nail, or even transversely, parallel to the free edge (Fig. 2A).

In contrast, cracks readily propagated in the transverse orientation around the nail, following the curvature of the free edge and lunula (Fig. 2B). Cracks only deviated occasionally from this pathway in the dorsal layer of the nail, where the tear sometimes moved proximally, and the dorsal layer peeled off from the intermediate layer beneath.

Scissor cutting tests on whole nails

The results of the scissor cutting tests (Fig. 3A) enable us to understand why there were such differences in fracture properties in the two directions. The central sections of the nails were almost twice as tough in the longitudinal plane as in the transverse plane, a difference that the paired *t*-test showed to be highly significant (t_{13}=57.3, P<0.001). The outer sections were slightly less tough and showed a slightly lower (but still highly significant) degree of anisotropy (t_{13}=48.6, P<0.001).

Scissor cutting tests on individual layers

The results of the tests on individual layers (Fig. 3B) localised the anisotropy of the nail to the intermediate layer; it was almost four times as tough in the longitudinal plane as in the transverse plane, a difference that the paired *t*-test showed to be highly significant (t_8=27.7, P<0.001). In contrast both the dorsal and ventral layer showed essentially isotropic behaviour with low toughnesses in both the longitudinal and transverse planes. In neither were differences in toughness between the directions significant.

Scanning electron microscopy

Scanning electron microscopy of the transverse fracture surfaces (Fig. 4A–D) clearly revealed the three nail layers mentioned by other authors. They also showed that the layers differed markedly in structure, a fact that could further explain the results of the mechanical tests. The dorsal layer (seen most clearly in Fig. 4C) appeared to be composed of flat, overlapping slate-like sheets, which were oriented in the plane of the nail. In contrast the thick intermediate layer was more fibrous, with the fibres oriented transversely, parallel to the free edge of the nail. Finally, the thin ventral layer was more similar to the dorsal layer. The only difference in structure occurred at the edge of the nail (Fig. 4D), where the dorsal and ventral and bottom layers appeared to become thicker, producing a flat sheet, which wrapped around the outside to produce a smooth outer edge. The fracture surface itself was relatively smooth in the intermediate layer (Fig. 4A,B), where the line of failure followed the orientation of the fibres. In the dorsal and ventral layers, in contrast, the fracture surface was more jagged, the fracture surface being deflected around individual sheets. Sometimes the failure surface in the dorsal layer moved proximally relative to the fracture of the intermediate layer (Fig. 4B).

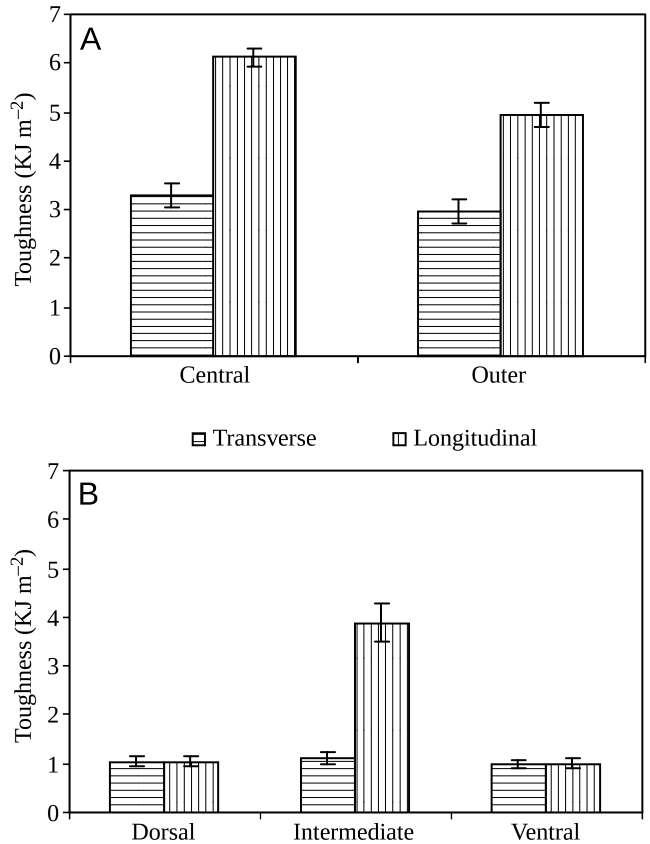

Fig. 3. Results of the cutting tests on nail clippings (A) giving the mean toughness (± S.D., N=15) of central and outer sections of the nail, when cut in the longitudinal and transverse directions and (B) showing the mean toughness (± S.D., N=10) of each of the three layers of the fingernail, when cut in the longitudinal and transverse directions.

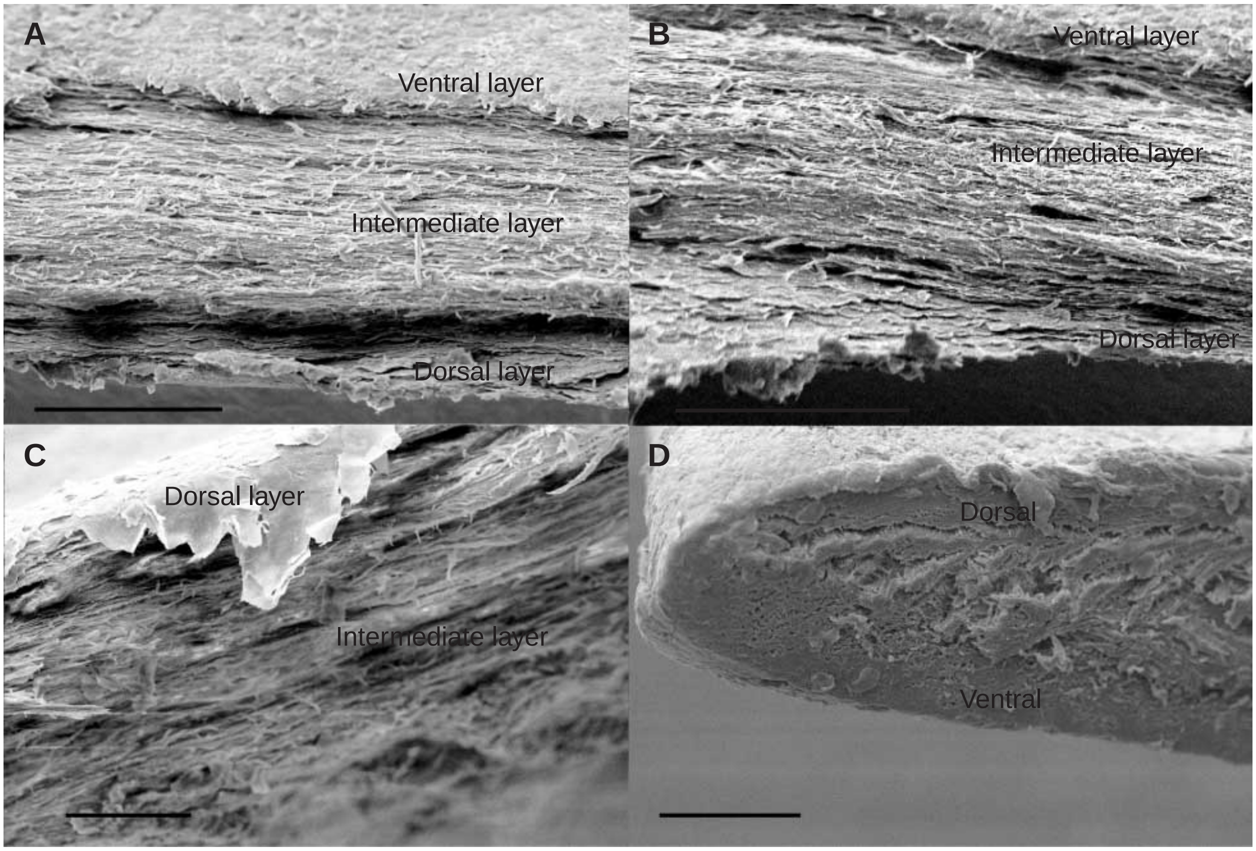

Fig. 4. Scanning electron micrographs of the fracture surfaces of torn nail clippings, with the main fracture surface running in the transverse direction. (A) In the central area of the nail, fracture follows the orientation of the keratin fibres within the thick intermediate layer. Fracture through the plate-like cells of the dorsal and ventral layers is more jagged. (B) Towards the edge of the nail (left), the failure through the dorsal layer often moves more proximally as it peels off the intermediate layer. (C) A close up of the plate-like dorsal layer and fibrous intermediate layer. (D) Lateral edge of the nail cut with scissors. The dorsal and ventral layers get thicker towards the edge and wrap around the end of the intermediate layer, helping prevent cracks forming. Scale bars, 200 μm (A,B), 100 μm (C,D).

Polarized light microscopy

Preferred fibre orientation was only detected in the intermediate layer, in which fibres were oriented in the transverse direction, parallel to lunula and hence to the long axis of the cells of which it was composed.

Discussion

The results of the tear tests showed that human fingernail has a remarkable ability to prevent cracks running longitudinally into the nail bed. This occurs firstly because human fingernail is a fairly tough material. Our tests gave toughnesses of approximately 3 and 6 kJ m^{-2} for the transverse and longitudinal directions, which are similar to the values of 5.5–7.8 kJ m^{-2} that Kasapi and Gosline (1997) found for horse hoof. As in horse hoof, the ability to deflect cracks into the transverse direction appears to be related to the anisotropy of the nail; cracks take only half the energy to propagate transversely compared with longitudinally.

Microscopy and toughness tests on the individual layers showed why this anisotropy occurred. The fracture properties of the nail are dominated by the thick intermediate layer, composed of long narrow cells, which are orientated laterally, parallel to the lunula and the free edge of the nail. Only around a quarter of the energy is needed to cut this layer transversely compared with longitudinally; a transverse cut just has to separate the cells whereas longitudinal cuts would have to cut through the cells. This pattern will therefore result in automatic trimming of the nail parallel to the lunula.

The anisotropy is somewhat reduced by the thin isotropic dorsal and ventral layers that are composed of tile-like cells with randomly oriented keratin fibres, particularly towards the edge of the nail where they become relatively thicker. So what are the functions of these layers? One effect they might have is to help increase the overall toughness of the nail by constraining the cells of the intermediate layer so that more of the cells have to be cut through rather than being separated during scissor tests. However, the reason why the toughness of the complete nail is greater than the average for the three layers may instead be due to a volume effect. Unlike in hair, cell walls are very conspicuous in nail (Baden, 1970) and it is possible that cutting through nail could cause them to buckle plastically, just like the cell walls of wood (Lucas et al., 1997). Thicker samples of nail would consequently be tougher than thin ones because the size of the plastic zone would be greater, just as in wood (Lucas et al., 1997).

The main purpose of the dorsal and ventral layers, however, is probably to resist longitudinal bending. These two layers, away from the neutral axis of the nail, are well placed to resist tensile and compressive forces in the longitudinal direction, which would be set up when the nail is bent upwards, and also to resist the transverse forces that might be set up by uneven loading of the nail. The forces would be strongly resisted by their randomly oriented keratin fibres. This interpretation is supported by Baden's findings (Baden, 1970) about the stiffness of human nail tissue. Using bending tests, he found that the bending modulus of nail, approximately 3–5 GPa, was similar in the transverse and longitudinal directions, a finding consistent with the idea that most of the bending load is resisted by the two isotropic outer layers that are set furthest from the nail's neutral axis. In contrast, measuring stiffness using the speed of sound through nail, he found that the Young's modulus was approx. twice as high (4.3±0.3 GPa) transversely as longitudinally (2.1±0.3 GPa). This probably occurred because the tensile and compressive properties of the nail would be dominated by the thick anisotropic intermediate layer.

The arrangement of fibres in the outer layers into tile-like cells also has a further advantage that they provide a smooth waterproof covering, which can protect the fibrous intermediate layer. Finally, there is one extra level of sophistication in the design. The dorsal and ventral layers wrap around the lateral edge of the nail, producing a smooth covering that prevents potentially dangerous cracks from forming there.

The whole design of the human fingernail leads to only two potential drawbacks, with which most readers may be only too painfully familiar! Because of the structure of the dorsal layer, in which the cells are packed like overlapping tiles, there is no preferred orientation for cracks to propagate in this tissue. This is why when you tear or bite your nails, the dorsal tissue will often delaminate from the intermediate layer and cracks in it will run towards the base of the nail (Figs 3B, 4B). This problem becomes particularly acute towards the lateral edges of the nail where the outer layers are thicker. They start to dominate the fracture properties of the nail in this region and cracks can start running proximally 'into the quick', causing damage to the soft skin along the lateral nail fold. Most people will be familiar with the bleeding around the edge of the nail, and the pain that results. The delamination of the tile-like dorsal surface also allows nails to chip relatively easily, spoiling their appearance and reducing their strength.

The principles of the mechanical design of fingernails also have important implications for nail care. In traditional manicures, nails are filed into a point rather than being cut parallel to the lunula. From a mechanical viewpoint one might expect this to be disastrous, because towards the point, the edge would not be protected by the wrapping round of the dorsal and ventral layers; cracks would therefore more readily form, and the nail would be more likely to break. One might also expect varnished nails to be more prone to destructive cracking than unvarnished ones. The hard outer layer would reduce the nail's toughness, just as an outer brittle lacquer greatly reduces the toughness of polymers (Atkins and Mai, 1985). The varnish, which is isotropic, might also dominate the fracture properties of the nail and so cracks might be able to run equally easily in all directions. Experimental work is needed to test these ideas, but it is clear that our increased understanding of nail mechanics could help to improve nail care and to develop novel nail care products and nail prostheses.

Clearly, this preliminary study has only started to scratch the surface of fingernail design. More needs to be known on the elastic properties of the three layers and their ultrastructure, as well as their toughness. More also needs to be known of inter-individual and interracial differences; the effects of disease and mineral deficiency; and the differences between fingernails and toenails. Finally, there is a need for interspecific comparisons, to investigate the changes in structure that accompanied the evolutionary changes in shape from the insectivore claw to the primate nail. The study of Baden (1970) also suggests there are substantial differences in fibre orientation between the nails of different primates, depending on the shape and curvature of their nails, differences which need to be investigated more thoroughly. Nonetheless this preliminary study *has* shown that human fingernails are extremely sophisticated structures, apparently well designed for their function, and that an understanding of the comparative functional morphology of nails and claws is well within our grasp.

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