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The effects of trapping and blade angle of notched dentitions on fracture of biological tissues

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SUMMARY

The material properties of food can exert a significant influence on tooth morphology. Although the stiffness or toughness of a material is usually of prime concern, other aspects of material properties (such as extensibility) can be of equal importance. Previous experimental work on the effect blade shape has on fracturing biological materials indicated a notched blade greatly reduced the work required to cut tough tissue. As a notched blade both traps materials and cuts at an angle, it is not clear which of these features leads to increased cutting efficiency. This paper tests whether the ability to cut at an angle or trap the material has the greater effect on the work to fracture required to cut tough tissues with different levels of extensibility (asparagus and fish muscle). Results show that the work to fracture required to cut more extensible materials is reduced by up to 50% when a trapping mechanism alone is used in comparison with an angled blade alone. For less extensible materials, the trapping ability of a notch seems to have no effect, whereas the angled blade reduces work to fracture by up to 25% relative to a straight blade. The aspects of blade shape most important to the breaking down of foods depend upon the relative stiffness or toughness, as well as other material properties.

Key words: blades, cutting, dentition, fracture, food breakdown.

INTRODUCTION

Understanding the relationship between the morphology of a biological feature and its emergent function is an essential part of the evolutionary sciences. Teeth and other dental features make a good test system for these types of questions, as they are at the immediate interface between the animal and its environment. A great deal of theoretical work has examined the relationship between tooth form and function in various mammalian groups (e.g. Freeman, 1992; Popwics and Fortelius, 1997; Evans and Sanson, 2003; Evans and Sanson, 2006) [see Anderson and LaBarbera (Anderson and LaBarbera, 2008) for a larger review]. Some experimental work has also been done on mammalian forms (Evans and Sanson, 1998; Freeman and Lemen, 2007) as well as studies of cutting ability in sharks (Frazzetta, 1988) and tooth serrations in dinosaurs and lizards (Abler, 1992). A good deal of work has been done on human dentition (e.g. Korioth et al., 1997; Agrawal and Lucas, 2002), although these latter studies are generally specific to the medical or food science industries (see Anderson and LaBarbera, 2008).

The material properties of food items can exert a significant influence on tooth morphology (Lucas, 2004). Food items can be defined in terms of Young's modulus (stiffness) and toughness, creating a continuum from brittle to tough materials (Lucas et al., 2002). Brittle materials have high stiffness, and often require high forces for fractures to initiate, but fail catastrophically when they do. Tough materials typically take less force to start a fracture, but require additional energy to continue fracture propagation. The ability of tough materials to 'blunt' fracture propagation is enhanced by increased extensibility (the average strain at fracture) and Poisson's ratio (Lucas, 2004). The Poisson's ratio relates how stress applied in one direction on a material affects the compression or tension in the other directions (Vogel, 2003).

A sharp bladed edge is the most effective method for cutting tough materials with high extensibility and high Poisson's ratios, as has been shown many times experimentally (Lake and Yeoh, 1978; Purslow, 1983; Pereira et al., 1997; Lucas and Peters, 2000). Bladed dental shapes are prevalent in nature including mammalian groups (Van Valkenburgh, 1989; Evans and Sanson, 2003), sharks (Frazzetta, 1988; Shirai and Nayakaya, 1992), along the beaks in edentate animals such as turtles (Davenport et al., 1992) and avian groups, and in extinct fossil groups (Anderson and Westneat, 2007; Anderson and Westneat, 2009).

In a previous paper, I experimentally tested the effects of v-shaped notched blades (Fig. 1D–F) *versus* straight blades (Fig. 1A) on the energy required to cut various tough prey materials (Anderson and LaBarbera, 2008). Previous hypotheses suggest that having a v-shaped notched blade should reduce the energy required to cut tough materials, such as flesh, with high extensibility and Poisson's ratio relative to straight bladed edges (Lucas, 2004). I developed a unique double guillotine testing device and used it to measure the work expended to fracture various biological materials, using both straight and notched blades. For most of the materials, using notched blades significantly reduced the work to fracture (Anderson and LaBarbera, 2008) supporting the initial hypothesis.

Although this study supports the idea that notched blades are more effective at fragmenting tough, extensible materials, the reason for this is unclear. Lucas' initial hypothesis (Lucas, 2004), suggested a bladed notch (Fig. 1D) will trap extensible materials with high Poisson's ratios, allowing them to be cut more easily. Using straight blades (Fig. 1A), the material will deform and spread beyond the blades, preventing a clean cut (Lucas, 2004). However, when a straight blade is replaced by a notched blade, the morphology changes in two ways: a 'trap' for the material is created, but the approach angle of the bladed edges is also altered (Evans and Sanson, 2003). The altered approach angle might be the key factor in reducing work to fracture measured in notched blades. Abler (Abler, 1992) suggested that the notched design seen in the bladed carnassial teeth of mammals has the primary effect of forcing the material against the angled bladed edges of the teeth, a combination of the 'trap' and approach angle interpretations.

Although initially chosen as a 'simple' variable, a notched blade is a quite complex tool. Two factors could enable its ability to cut with less energy. One advantage of the test design outlined in the previous paper (Anderson and LaBarbera, 2008), is that it is possible to test these different interpretations experimentally, and evaluate which aspects of the v-shaped notched blades caused the reduction in energy expended. Using an improved version of the original double guillotine testing device, I have tested whether altering the approach angle of the blades or simply adding a 'trap' to straight blades has a larger effect on the energy required to fragment extensible biological materials. I also tested the effects of blade design on materials with different levels of extensibility.

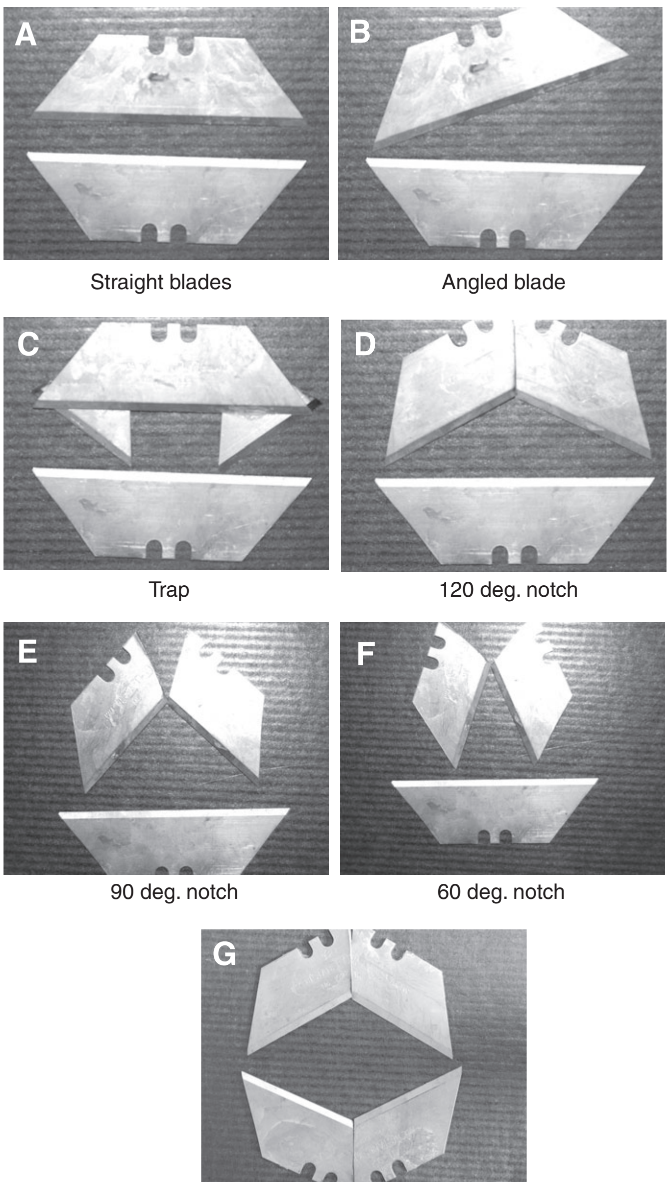

Fig. 1. The seven blade configurations used in this study. (A) Two straight blades opposed to each other. (B) A blade set at a 60 deg. approach angle opposed to a straight horizontal blade. (C) Two straight blades with an added blunt barrier to trap the test materials. (D) A 120 deg. bladed notch opposed to a straight blade. (E) A 90 deg. notch opposed to a straight blade. (F) A 60 deg. notch opposed to a straight blade. (G) Two paired 120 deg. notched blades opposed to each other. In all configurations, the test material was placed between the blades, centred along the upper edge.

MATERIALS AND METHODS

Double guillotine

There are two general types of testing machines used to measure the toughness (or work to fracture) of materials such as biological tissues: the single blade guillotine (Atkins and Mai, 1979; Veland and Torrissen, 1999) and the scissors tests (Pereira et al., 1997; Lucas, 2004). The double guillotine device previously developed (Anderson and LaBarbera, 2008) combines these two ideas, resulting in a machine that features two blades opposed to each other (as in a scissors test) that can easily be replaced with different blade shapes as needed (as in a guillotine). Ang et al. (Ang et al., 2008) questioned the use of double-bladed tests for measuring work to fracture in biological tissues, citing difficulties with obtaining clean cuts. These points are valid but primarily concerned with obtaining accurate, repeatable measurements of the material properties of thin tissues. For this study, I was more concerned with the effects of different cutting morphologies on fracture mechanics, so difficulties associated with obtaining clean cuts are useful and important data for analyses.

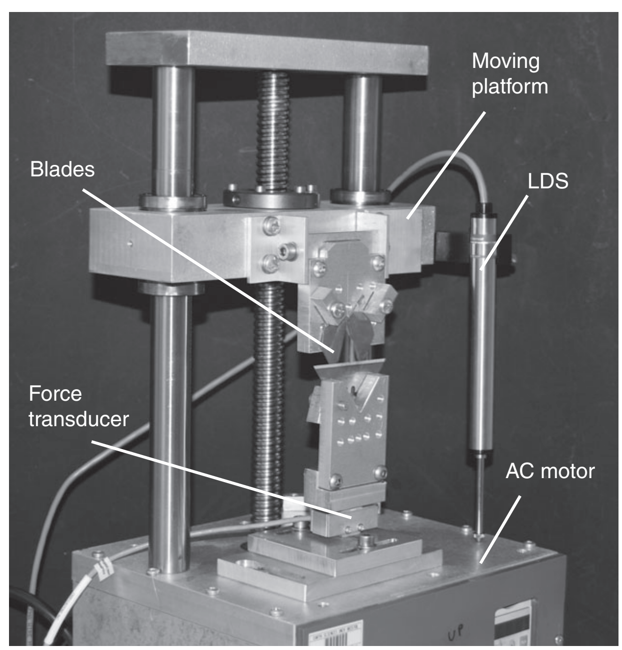

Fig. 2. New double guillotine testing device designed by the author and M. Dury. The AC motor housed within the metal box drives a screw which moves the upper platform relative to the base. Materials are cut between the two mounted blades, and the forces exerted by fracture creation are measured by the force transducer. Displacement is measured using a mounted linear displacement sensor (LDS).

For this study, I utilized a new double guillotine design (Fig. 2). The entire machine was set into a stable box base, housing an AC induction motor and gearbox (Parvalux, SD18M, Bournemouth, UK). The bottom blade was stationary and mounted on top of the box, blade edge oriented upwards. The upper blade was mounted onto a separate platform attached to the top of the box by a large screw (SKF, 20 mm diameter, 3 mm pitch; Fig. 2). The rotation of the screw, and the subsequent movement of the upper platform, was driven by the AC motor, ensuring a constant velocity ($1.9\,\mathrm{mm\,s^{-1}}$; the default setting) for every experiment. The mounting apparatus for the two blades was built to handle a complex range of positions, allowing for different rake and approach angles as well as precise alignment of the opposing blades to pass each other. The lower blade was mounted onto a force transducer (LC703-100; Omegadyne, Inc., Sunbury, OH, USA) and a LDS sensor (HS50 Linear Displacement Sensor; Vishay, Measurements Group UK Ltd, Basingstoke, UK) was used to measure the displacement of the upper platform during cutting. The signals from these sensors were detected and amplified by a Vishay 5000 series 5100B Scanner (Vishay), which automatically converts the electrical signal into force and displacement based on factory-set calibrations of the sensors (verified manually).

Blades

Stanley Pre-sharpened carbon steel utility blades were used as dental tools. V-shaped blades (Fig. 1D–F) were created by cutting the steel blades in half at pre-determined angles using a hand-held grinder. Both whole blades and machined notched blades were mounted onto steel holders using cyanoacrylate adhesive (Procure PC 06, Cyanotec, Kingswinford, UK). Machined blades were oriented on the steel holders to create v-shaped bladed notches at a variety of angles (Fig. 1D–F). The blades were adjusted such that the two opposing edges move just past each other without noticeable friction. The clearance is approximately 0.13 mm. I tested for frictional forces by taking force measurements of a test run with no material in between the blades. Any force measured was attributed to friction.

The null run set-up consisted of two straight blades aligned parallel to each other with material held between the blade edges (Fig. 1A). A standard bladed notch set-up was arranged with the manufactured v-shaped notch suspended above a normal straight edged blade (Fig 1D–F). In all tests the upper notch was the mobile blade [previous test analyses indicated that whether the notch was the upper moving blade, or lower stable blade makes no difference in the results (Anderson and LaBarbera, 2008)]. To test the effects of the approach angle alone, I used a straight edged lower blade paired with an upper straight blade mounted at an approach angle of 60 deg. (Fig. 1B). To create a 'trap' set-up, I mounted two straight blades parallel to each other, as in the reference situation, with two non-edged pieces of steel (the backs of scrap blade pieces) attached to the upper blade so as to create a restricted 'trap'. The trap prevented deformation laterally along the blade edge (Fig. 1C). To further test notch effects, I used a final set-up consisting of two machined notched blades oriented so that the space in between resembled a diamond shape (Fig. 1G). This particular set-up was similar to that seen in the carnassials of certain mammals (Abler, 1992).

Test materials

For this study, I used raw salmon flesh purchased from the local grocery store (Sainsbury's own brand skinless, boneless fillets) as the test material. Using the initial guillotine system, the work to fracture required to cut salmon flesh did not significantly vary when different blade types were used (Anderson and LaBarbera, 2008). Initial tests on salmon muscle using the new guillotine (outlined below and reported in the results) did show significant differences. I diced the salmon into approximately $1\,\mathrm{cm^3}$ chunks for testing with minimal connective tissue. Pieces of flesh were held between the blades of the guillotine for cutting, and oriented with the muscle fibres perpendicular to the bladed edges. Aligning the flesh in such a way ensured that the experimental set-up was repeatable.

For comparison, I also tested store-bought asparagus spears. Although plant materials can be considered tough and fibrous, they are much less extensible and have lower Poisson's ratios than animal tissues (Lucas, 2004). This is the result of their cellular construction (Wilsea et al., 1975). Asparagus was selected as a test material because of its availability at the local grocery store, ease of use with the guillotine and suitable cross sectional area. I trimmed the asparagus spears such that all experimental cuts were made along a restricted length of the spear with consistent diameters. This ensured minimal change in material properties of different parts of the stalk.

To verify the differences in Young's modulus and Poisson's ratio, I performed uniaxial compression tests of both materials using a miniature computer-controlled materials testing machine (Minimat 2000, Rheometric Scientific Inc., Piscataway, NJ, USA).

Analysis

Work to fracture ($\mathrm{J\,m^{-2}}$) is a size-independent measure of the work required to create a surface of unit area on a material (Atkins and Mai, 1985). In these experiments, work to fracture is the work done while cutting the test material divided by the surface area created. The force transducer and LDS sensors measured the force produced during cutting and the distance covered by the moving upper blade, respectively. These measurements were directly converted into their calibrated units by StrainSmart software (Vishay Measurements Group UK Ltd). I plotted the force *versus* displacement curve and calculated the area under this curve, which is a measure of the work done during cutting. This work measurement was divided by the area of the cut surface created in the test material in order to calculate work to fracture. I also collected peak force measurements (N) during each experiment.

Fig. 1 illustrates the various blade set-ups used in this study. I performed two separate sets of tests. For the first set of tests, I analyzed salmon flesh using the same four blade set-ups used in the previous study (Anderson and LaBarbera, 2008): straight blades (Fig. 1A) and notched blades set at 120 deg. (Fig. 1D), 90 deg. (Fig. 1E) and 60 deg. (Fig. 1F) angles. I also tested salmon between two opposed notched blades set at 120 deg. (Fig. 1G). The second set of experiments tested the main hypothesis concerning the effect of approach angles and trapping ability. I tested both salmon flesh and asparagus stalks using four blade set-ups: straight blades (Fig. 1A), an angled blade (Fig. 1B), straight blades with a 'trap' (Fig. 1C), and a 120 deg. notch (Fig. 1D). I performed tests on salmon using straight blades and 120 deg. notches twice because of possible changes in the material properties of the flesh after freezing between the two sets of experiments. I repeated all combinations of prey material and blade arrangement seven to 12 times per experiment set.

The work to fracture and maximum force values from each repeated experiment were used to calculate average work to fracture and peak force values for each combination of material and blade configuration. The average values were then compared using one-way ANOVA tests with Bonferroni *post-hoc* tests to compare specific configurations (using SPSS statistical software package for Mac [OS X]).

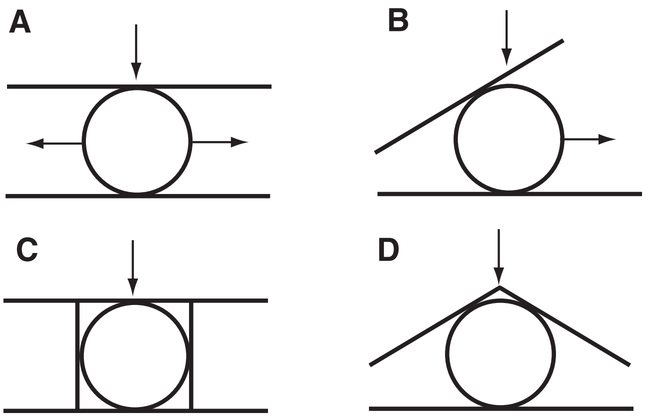

Fig. 3. Sketches illustrating the deformation of salmon muscle during cutting experiments under four different blade configurations. (A) Two straight blades. Salmon muscle deforms in two directions, delaying fracture and dissipating a large amount of energy. (B) A 60 deg. approach angle. Although the salmon fractures with less energy, it still deforms as the blade literally pushes the material in one direction. (C) 'Trap' configuration. (D) A 120 deg. notched blade. Both C and D show no deformation along the bladed edge because the material is trapped between barriers.

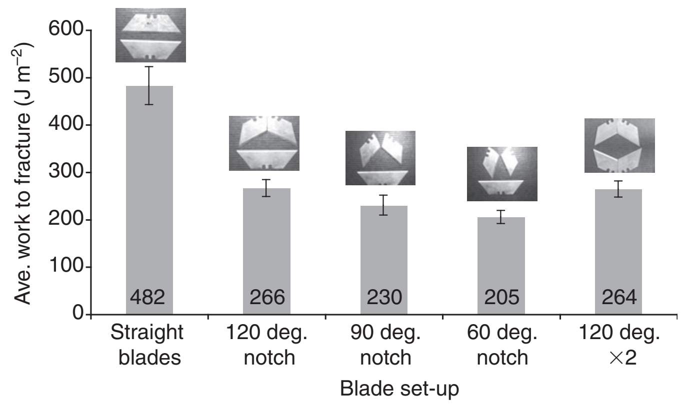

Fig. 4. Comparison of the effect of notched blades and their angle on the average work to fracture of salmon muscle. Average work to fracture values (in J m^{-2}) for each set-up are listed at the base of the bars. Error bars represent ±1 s.d.

RESULTS

Material properties

Simple uniaxial compression tests on chunks of salmon flesh resulted in an estimated Young's modulus of 1.25 kPa and Poisson's ratio of around 0.4. By comparison, asparagus shows an estimated Young's modulus of 132.5 kPa and a Poisson's ratio of 0.2.

Qualitative cutting patterns

Similar cutting patterns were seen in salmon flesh as have been reported previously for straight and notched blades (Anderson and LaBarbera, 2008). The salmon flesh was initially pinched by the two straight blades (Fig. 1A), and spread along the blade edge until the blades passed each other vertically, at which point fractures initiated and grew along both bladed edges (Fig. 3A). When only the approach angle was used (Fig. 1B), fracture in the salmon flesh initiated earlier than when the paired straight blades were used; however, there was still notable deformation along the blade edge as the descending blade pushed the material laterally (Fig. 3B). In the 'trap' scenario (Fig. 1C), the blunt boundaries prevented the flesh from spreading along the edge, and fracture initiated earlier than with paired straight blades alone (Fig. 3C). In the notched blade configuration (i.e. 120 deg. notched blades, Fig. 1D), cutting was initiated much earlier than in the straight blade configuration with less overall deformation and was almost complete along the angled notched blades (Fig. 3D). For the asparagus tests, fracture proceeded with much less deformation along the edges regardless of the blade set-up applied.

Quantitative results – force and work of fracture

Fig. 4 illustrates how average work to fracture values for salmon muscle compare between the various blade configurations for the first set of experiments. Any notched blade set-up significantly reduced the work to fracture by up to 60%, compared with the straight blade set-up (ANOVA: $F_{4,47}$=12.575, P<0.001). However, none of the notched blade angles produced significantly different work to fracture results from each other. This includes when two notched blades were set opposed to each other (Fig. 4).

Variations in work to fracture values for similar blade set-ups between the two experiment sets (120 deg. notched blade set-up in both Fig. 4 and Fig. 5A) is due to changes in the material properties of salmon after freezing. To account for this, all set-ups to be compared were tested on the same day at the same time.

Fig. 5A illustrates the work to fracture results of the second set of experiments (angled blades *versus* a trap) with salmon muscle (ANOVA: $F_{3,38}$=27.132, P<0.001). Both the angled blade and trap set-ups reduced work to fracture compared with straight blades (Fig. 5A; P<0.001); however, the trap set-up reduced work to fracture by a larger amount (P<0.05), equivalent to the reduction of a 120 deg.

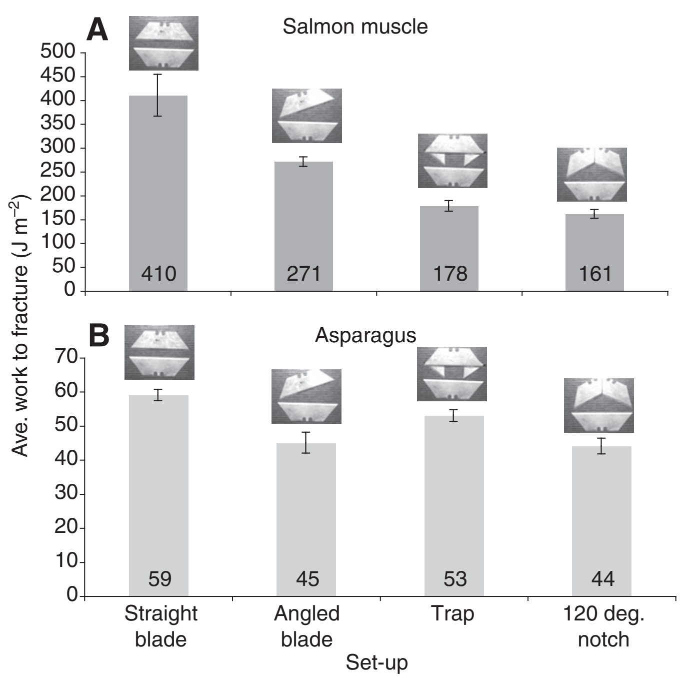

Fig. 5. Work to fracture for salmon muscle (A) and asparagus stalks (B), comparing the effects of approach angle *versus* trap ability. Average work to fracture values (in J m^{-2}) are listed at the base of each bar. Note the order of magnitude difference in values between the two materials. Error bars represent ±1 s.d.

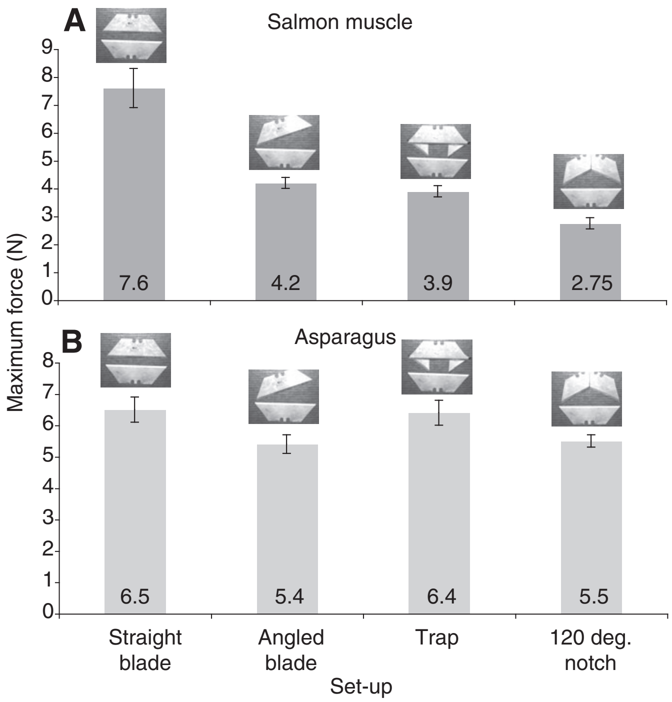

Fig. 6. Maximum force measurements for salmon muscle (A) and asparagus stalks (B), comparing the effects of approach angle *versus* trap ability. Maximum force values (in N) are listed at the base of each bar. Error bars represent ±1 s.d.

notch set-up. Maximum force measurements followed a similar pattern (ANOVA: $F_{3,38}$=29.952, P<0.001; Fig. 6A).

Fig. 5B shows the results with asparagus, in the same set of blade configurations as for the salmon in Fig. 5A (ANOVA: $F_{3,32}$=10.727, P<0.001). Note that an order of magnitude difference exists between the work to fracture values in Fig. 5A and B. Only the angled blade and 120 deg. notch set-ups reduced work to fracture compared with the straight blades (P<0.005). The trap set-up did not reduce work to fracture significantly. Maximum force measurements show a similar pattern (Fig. 6B); however, there was no significant differences between any of the set-ups (ANOVA: $F_{3,32}$=2.626, P=0.067).

DISCUSSION

The experiments in this study suggest that the ability to constrain tough, extensible materials during cutting is an important factor in reducing the energy expended while masticating. These results were found using a new double guillotine testing system and they indicate that a notched blade does affect the work to fracture measured during cutting of salmon muscle, unlike results obtained using an older system (Anderson and LaBarbera, 2008). This disagreement may be due to inconsistency in the cutting speed of the old system (manually driven by a crank), which can produce significant variation in the work to fracture measured for salmon muscle (ANOVA: F=11.044, P<0.001). Cutting salmon muscle requires low work to fracture to start with (Anderson and LaBarbera, 2008) (Fig. 4 and Fig. 5A this paper). Variation in speed could be enough to obscure the differences in work measurements of the different blade morphologies. In the new system, the blade movement is driven by a motor and held constant, eliminating this extra variable and any variation in measurements it might cause.

The results presented here support Lucas' hypothesis (Lucas, 2004) that having a notched blade constrains or 'traps' extensible materials, which reduces the energy lost due to deformation and allows fracture to occur at a lower level of work. Adding blunt, vertical boundaries to a pair of straight blades (Fig. 1C) reduces the energy needed to cut salmon muscle by up to 70%, equivalent to using a 120 deg. notched blade (Fig. 5A). In fact, using only a blade with an equivalent approach angle to the 120 deg. notch, but without a 'partner' to aide in trapping (Fig. 5A) was not as effective. Altering the approach angle of a blade did reduce the work required to cut salmon flesh by up to 40% compared with straight blades (Fig. 5A), a substantial advantage to carnivorous animals needing to fracture tough, extensible tissues, but not as effective as the trap configuration. It is just as important to be able to trap and restrict the deformation of the material during cutting. These results support previous hypotheses about the ability of carnivores to trap meat in order to aide in mastication, particularly concerning serrations (Abler, 1992; Lucas, 2004).

The results of this study show that the material properties of the prey item being cut determine what sort of dental tools result in the smallest work to fracture values. For salmon flesh, which has low stiffness (1.25 kPa) but a high Poisson's ratio (0.4), the trapping ability of a notched blade is important to reducing energy while cutting. However, a 'trap' attached to straight blades has no effect on work to fracture of asparagus, a material with a much lower Poisson's ratio (0.2). For the asparagus, the altered approach angle is the most important factor, reducing work to fracture just as effectively as a notched blade set-up (Fig. 5B). Previous work showed how the relative brittleness and toughness of food determine the most effective tooth shape (Lucas, 2004; Anderson and LaBarbera, 2008). This study shows that there are aspects of materials beyond the brittle/tough dichotomy which are important, such as the Poisson's ratio. Friction probably plays a role in the interactions between blade and food as well, although the precise nature of theses interactions is unclear.

In his paper on the morphology of serrations and their effect on soft tissues, Abler (Abler, 1992) mentioned another aspect of notched blades, which deserves attention here. The carnassial tooth morphology found in many mammalian carnivores essentially comprises two bladed notches opposed to one another (Fig. 1G). This orientation allows the teeth to mimic the action of scissors. As the two notched blades pass each other, the angled edges cross on either side and create a scissoring motion (Fig. 1G) (Abler, 1992). Abler argued that this scissoring action would only contact a small portion of the material, even as the space between the blades closed making it an inefficient way to cut (Abler, 1992). He suggested that the carnassial morphology cut more easily by increasing the pressure along the edges of the blades. This increased pressure was partly caused by the approach angle, and partly by the v-shaped morphology forcing the material against the edges (Abler, 1992). The results of the study presented here support Abler's assertion in several ways. Both the approach angle (Fig. 1B) and the 'trap' (Fig. 1C) configurations resulted in reduced work during cutting, supporting their importance in carnassial morphology (Fig. 5A). However, it did not matter what angle the notched blades were set at, nor whether the notched blade was opposed to another notched blade (Fig. 1G) or just a straight edge (Fig. 1D) in terms of the amount of work measured (Fig. 4). These latter results indicate that the actual 'morphology' of the scissors (the angle at which the two opposed blades cross) does not seem to have any effect on measured work to fracture.

Even seemingly simple variations in dental tool shape can have complex effects on cutting ability. Using a notched blade as opposed to paired straight blades can reduce the energy required to cut both plant materials (asparagus) and extensible animal material (salmon muscle). However, the reason for this is different in the two foodstuffs. Trapping ability seems to make the largest difference when dealing with extensible materials with high Poisson's ratios such as animal flesh, but the approach angle appears to most affect the asparagus. The interplay between tooth form and the material properties of prey materials is a complex one that requires a more thorough investigation. Tests on a wider variety of prey materials are required to fully understand the spectrum of challenges facing teeth in trying to break down food. Studies using the double guillotine device have so far focused solely on two-dimensional aspects of tooth shape in an effort to simplify the problem. Future studies utilizing this device will focus on three-dimensional aspects of tooth shape and their potential to break down biological tissues with varying material properties.

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