CARTIALGE FRACTURE TOUGHNESS BY MICROPENETRATION

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INTRODUCTION

Cartilage strength is important for cartilage function, since loss of strength leads to tissue breakdown and loss of function. Although an important property, there are few methods for measuring cartilage strength. Tensile tests are the most common method, but they do not reflect the failure mode of cartilage, which is more a crack propagation process [1], and it is difficult to fabricate the small specimens needed for these tests. An alternative method for strength measurement is micropenetration, in which a sharp tip penetrates the tissue surface, while force and displacement are measured. Small tissue volumes can be tested without the need to prepare regularly shaped small specimens. Current nanoindentation methods applied to metals provide a measure of elastic modulus and hardness [2]. Although powerful, these methods cannot be applied to soft tissues. Methods are proposed for overcoming these limitations and deducing a fracture toughness value for cartilage from micropenetration tests. The goal of this work is to describe the method and validation experiments in which predicted penetration depth and fracture toughness are compared with independent measures.

METHODS

Cartilage from bovine patella was indented using a NanoindenterXP (MTS, Inc.). Specimens ~10 x 10 x 4 mm were adhered to a holder and bathed with PBS. The top ~2mm was cartilage while the bottom was bone. Indents were made with a conical indenter with diamond tip of included angle of 67^0. The diamond tip was blunted, with radius of approximately 10 µm. After finding the surface, the tissue was loaded at a rate of 4 mN/sec to a maximum load. To assess penetration, in test Group 1 indents with maximum loads of 75, 100, 150, 200, 300, and 400 mN were performed. After testing the cartilage was bathed in India Ink and examined in a dissecting microscope. In each of Groups 2 and 3, 3 indents each of maximum load of 300 mN and 400 mN were performed. In group 4, 3 indents of 300 mN and 3 indents of 400 mN were performed and the specimen prepared for histology and depths of the indents measured from the slides. Histology of Group 3 was also performed.

Depth of penetration was predicted by assuming that the rate of work done, the power, increases rapidly whenever penetration occurs. After an initial penetration, as determined from the power rate, all displacement that occurs during elevated power rate was considered penetration displacement. These were summed to give the total penetration. The penetration, or fracture work, done was the sum of work done during the penetrating displacements. Fracture toughness was defined as the work during penetration divided by one-half the penetrated surface area of the conical tip.

RESULTS

The predicted depth of penetration was not different from the depth measured by histology for either the 300 mN indents (N=6 for predicted; N=5 for histology) or the 400 mN indents (N=6 for predicted; N=6 for histology) ($p>0.5$), although there was more scatter in the 400 mN data (Figure 1). Comparing the power and India Ink stain images indicated that rapid change in the power was a reliable indicator of penetration.

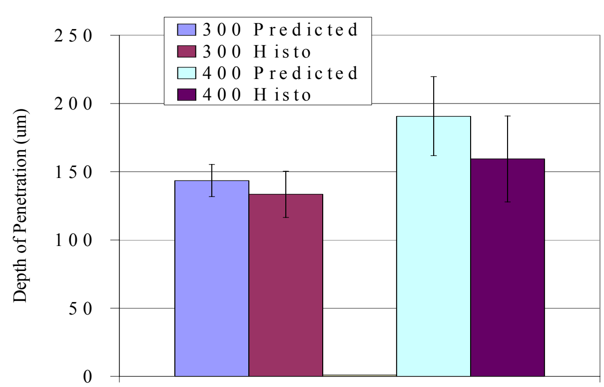

Figure 1: Penetration depth predicted by the method and measured by histology.

The predicted fracture toughness for the 300 mN indents was the same as the predicted fracture toughness for the 400 mN indents, for both groups 2 and 3 (Figure 2). The pooled results for Group 2 were different from the results for Group 3 ($p<0.01$), probably reflecting variation over the patella surface. The fracture toughness of Groups 2 and 3 were pooled and compared to the fracture toughness of bovine cartilage measured by Adams et al. [3] using a modified single edged notch test. There was no difference between the Adams et al. results and present results (Figure 2).

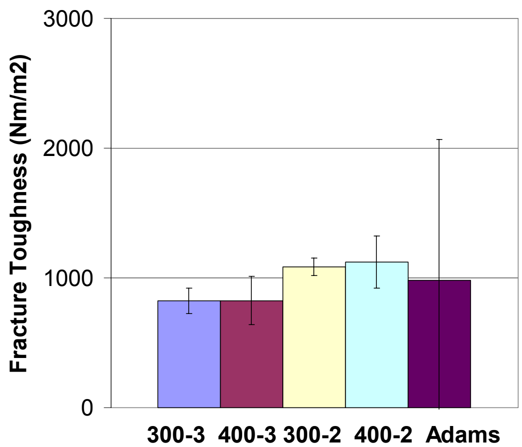

Figure 2: Predicted fracture toughness for 300 and 400 mN maximum load, and as measured by Adams et al. [3].

DISCUSSION

For the conditions of this test, the method predicted depth of penetration and fracture toughness in good agreement with values measured by independent methods, supporting the validity of the proposed method for measuring fracture toughness of cartilage. Potential limitations of the method include dependence of the occurrence of ‘rapid work’, which in turn appears to be sensitive to tip geometry. Penetration with a sharp (radius of curvature less than 1 um) diamond tip did not show the same ‘rapid work’. Further work is needed to optimize and understand the effect of tip geometry. The assumption of a crack equivalent to one-half the cone geometry is not strictly true, since the defect often has multiple cracks emanating from a central site. The method can be thought of as normalizing the penetration work to the penetrated cone geometry.

The method samples tissue of the order of several hundred microns in depth, within the superficial region of the cartilage. Results may be dependent on depth of penetration. In spite of these potential limitations, the method is promising as a way to measure the strength of small regions of cartilage.

REFERENCES

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