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Research Paper

A comparison of stress in cracked fibrous tissue specimens with varied crack location, loading, and orientation using finite element analysis

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ABSTRACT

Cracks in fibrous soft tissue, such as intervertebral disc annulus fibrosus and knee meniscus, cause pain and compromise joint mechanics. A crack concentrates stress at its tip, making further failure and crack extension (fracture) more likely. Ex vivo mechanical testing is an important tool for studying the loading conditions required for crack extension, but prior work has shown that it is difficult to reproduce crack extension. Most prior work used edge crack specimens in uniaxial tension, with the crack 90° to the edge of the specimen. This configuration does not necessarily represent the loading conditions that cause in vivo crack extension. To find a potentially better choice for experiments aiming to reproduce crack extension, we used finite element analysis to compare, in factorial combination, (1) center crack vs. edge crack location, (2) biaxial vs. uniaxial loading, and (3) crack–fiber angles ranging from 0° to 90°. The simulated material was annulus fibrosus fibrocartilage with a single fiber family. We hypothesized that one of the simulated test cases would produce a stronger stress concentration than the commonly used uniaxially loaded 90° crack–fiber angle edge crack case. Stress concentrations were compared between cases in terms of fiber-parallel stress (representing risk of fiber rupture), fiber-perpendicular stress (representing risk of matrix rupture), and fiber shear stress (representing risk of fiber sliding). Fiber-perpendicular stress and fiber shear stress concentrations were greatest in edge crack specimens (of any crack–fiber angle) and center crack specimens with a 90° crack–fiber angle. However, unless the crack is parallel to the fiber direction, these stress components alone are insufficient to cause crack opening and extension. Fiber-parallel stress concentrations were greatest in center crack specimens with a 45° crack–fiber angle, either biaxially or uniaxially loaded. We therefore recommend that the 45° center crack case be tried in future experiments intended to study crack extension by fiber rupture.

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1. Introduction

Cracks in fibrocartilage are a common affliction with potentially severe consequences. In the intervertebral disc annulus fibrosus, cracks (i.e., tears) occur as the disc degenerates, causing pain or mechanical disruption (Osti et al., 1992; Vernon-Roberts et al., 2007; Haughton et al., 2000; Lee et al., 2004; Peng et al., 2005; Videman and Nurminen, 2004). Overload of the knee meniscus, such as in sport-related injuries, can also create cracks (Isaac et al., 2010; Drosos and Pozo, 2004; Fox et al., 2015; Snoeker et al., 2013). Meniscus cracks cause pain, compromise knee motion and, most importantly, promote osteoarthritis (Englund et al., 2012; Bedi et al., 2010; Mononen et al., 2013; Maffulli et al., 2010; Berthiaume et al., 2005; Lento and Akuthota, 2000; Lohmander et al., 2007). Furthermore, cracks in avascular fibrocartilage have poor healing potential (Arnoczky and Warren, 1983).

Cracks can grow quickly, so the future risk posed by a given crack is not necessarily obvious. A crack creates a stress concentration at its tip that facilitates local failure and thus crack extension (fracture) (Anderson, 2005). Even a small, asymptomatic crack may consequently be cause for concern. However, the mechanisms and mechanical loading conditions required for crack extension in fibrocartilage (and other fibrous soft tissues) are still largely unknown.

It has proven very difficult to produce crack extension in ex vivo mechanical testing. Only a few publications report fracture toughness for fibrous soft tissue (Purslow, 1985; Stok and Oloyede, 2007; Chin-Purcell and Lewis, 1996; Oyen-Tiesma and Cook, 2001; Koombua et al., 2006; Beatty et al., 2008; Wu et al., 2006). Taylor et al.'s (2012) review of these studies indicated that most did not actually produce fracture. Von Forell et al. (2014) noted a lack of crack extension in their fracture tests of Achilles tendon and anterior longitudinal spine ligament. Although fracture is not necessarily a relevant failure mode for all fibrous tissues (Taylor et al., 2012), cracks in fibrocartilage clearly do grow in vivo. Fracture cannot be studied directly in controlled conditions without an experimental protocol that actually produces crack extension. Identifying good loading conditions for crack extension is consequently quite important.

The absence of crack extension in most experiments may be caused by loading conditions that do not sufficiently represent in vivo conditions. The fracture tests cited above were all done using edge-cracked specimens in uniaxial tension, with the crack perpendicular to the edge of the specimen. In contrast, in vivo cracks (1) are often situated in the middle of the tissue, (2) are loaded multiaxially, and (3) come in a variety of orientations (Shieh et al., 2013; Swenson and Harner, 1995; Osti et al., 1992; Kawamura et al., 2003; McNally and Adams, 1992; Yoder et al., 2014).

The objective of this study was to identify new test configurations that are more likely to produce crack extension than uniaxially loaded edge crack specimens. Finite element analysis (FEA) was used for this search because the search space is very large. FEA also allows the application of previously validated models for tissue mechanics to estimate fracture risk. This approach cannot show that a specimen will definitely fracture, but it does identify the configurations most likely to produce fracture based on our current understanding of tissue elasticity. These configurations can then be specifically targeted in future work with physical specimens.

In this study, we compare specimens with varying (1) crack location (center vs. edge), (2) loading (uniaxial vs. biaxial), and (3) crack–fiber angle. The likelihood of fracture was compared using the magnitude of the crack-induced stress concentration. Greater stress was interpreted as greater fracture risk. Since fibrous tissue has multiple failure mechanisms, including fiber rupture, matrix rupture, and fiber sliding, fracture risk was evaluated separately for fiber-parallel, fiber-perpendicular, and fiber shear stress.

We hypothesized that at least one of the test configurations would have a greater stress concentration (a greater risk of fracture) than uniaxially loaded edge crack specimens. Our results partially supported this hypothesis. Center crack specimens with oblique crack–fiber angles produced more fiber-parallel stress, and thus a greater likelihood of fiber rupture, than edge crack specimens. Still, edge crack specimens produced large amounts of fiber-perpendicular stress (matrix rupture) and fiber shear stress (fiber sliding).

2. Materials and methods

2.1. *Specimen geometry and loading*

The specimen geometry was a 1 mm thick plate, which was meant to represent typical tensile test specimens. Through-thickness slit cracks were created either in the center or edge of the plate. The center crack meshes were 20 mm × 20 mm × 1 mm, with a 2 mm long crack, and the edge crack meshes were 10 mm × 20 mm × 1 mm, with a 1 mm long crack (Fig. 1). All cracks thus had a characteristic crack length of 1 mm (Janssen et al., 2002).

Uniaxial or biaxial tensile stretch was applied by displacing the edge nodes. Biaxial stretch was chosen because it is a standard test procedure for multiaxially loaded tissue (Sacks and Sun, 2003; Bass et al., 2004; O'Connell et al., 2012). Thus, three combinations of crack location and loading were examined: center crack biaxial (CCB), center crack uniaxial (CCU), and uniaxially loaded single edge notch (SENT) (Fig. 1).

In all cases, the stretch ratio in the fiber direction was set to 1.14. The CCB case was stretched equibiaxially in the xy plane. The uniaxially loaded cases were stretched parallel to the fiber axis, and the fiber-perpendicular axis was free to contract. This stretch ratio was chosen to fully load the simulated fibers, such that the resulting stress (~70 MPa) would be the same order of magnitude as fibrous tissue strength (LaCroix et al., 2013; Green et al., 1993; Skaggs et al., 1994; Holzapfel et al., 2005; Ebara et al., 1996; Tissakht and Ahmed, 1995).

2.2. *Crack–fiber angle*

For each configuration, the crack angle was varied relative to the fibers from 0° (parallel to the fiber axis) to 90° (perpendicular to the fiber axis). This variation was done in 15° increments. There is one exception: the SENT specimen has no 0° SENT case, as in that case the crack line and specimen edge would coincide.

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