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Dependence of nanoscale friction and adhesion properties of articular cartilage on contact load

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ABSTRACT

Boundary lubrication of articular cartilage by conformal, molecularly thin films reduces friction and adhesion between asperities at the cartilage–cartilage contact interface when the contact conditions are not conducive to fluid film lubrication. In this study, the nanoscale friction and adhesion properties of articular cartilage from typical load-bearing and non-load-bearing joint regions were studied in the boundary lubrication regime under a range of physiological contact pressures using an atomic force microscope (AFM). Adhesion of load-bearing cartilage was found to be much lower than that of non-load-bearing cartilage. In addition, load-bearing cartilage demonstrated steady and low friction coefficient through the entire load range examined, whereas non-load-bearing cartilage showed higher friction coefficient that decreased nonlinearly with increasing normal load. AFM imaging and roughness calculations indicated that the above trends in the nanotribological properties of cartilage are not due to topographical (roughness) differences. However, immunohistochemistry revealed consistently higher surface concentration of boundary lubricant at load-bearing joint regions. The results of this study suggest that under contact conditions leading to joint starvation from fluid lubrication, the higher content of boundary lubricant at load-bearing cartilage sites preserves synovial joint function by minimizing adhesion and wear at asperity microcontacts, which are precursors for tissue degeneration.

1. Introduction

The lubrication function of articular cartilage is essential for maintaining tissue health and preventing disease and damage such as osteoarthritis. While articular cartilage is lubricated by mixed modes of lubrication (Lewis and McCutchen, 1959; Walker et al., 1968; Unsworth, 1991; Gleghorn and Bonassar, 2008) in the presence of synovial fluid (Schmidt et al., 2007), boundary lubrication occurs under contact conditions of high load, low sliding speed, and/or reduced fluid viscosity. Under such interfacial conditions, the asperities on the opposing surfaces are separated only by a molecularly thin lubricant layer (Gleghorn and Bonassar, 2008), hereafter referred to as a boundary film. In most sliding systems operating under a range of loads and speeds, such as synovial joints where mixed modes of lubrication are encountered during a walking cycle, a sufficiently thick fluid film cannot be continuously maintained between the articulating surfaces. As a consequence, contact occurs at the higher summits of the countersurfaces, known as asperities. In the absence of fluid film lubrication, for example, when the sliding speed decreases to zero for motion reversal, the tribological behavior of reciprocating systems is controlled by asperity contact interactions (Bronzino, 2006; Neu et al., 2008; Winter, 2009). Thus, boundary lubrication conditions are unavoidable in synovial joints. The formation of a lubricious boundary film can be viewed as a last line of surface protection against solid-solid contact, which is precursor for high friction and excessive wear. Indeed, precocious joint degeneration has been observed in the absence of an effective boundary lubricant film (Marcelino et al., 1999; Jay et al., 2007).

The study of cartilage at the nano/microscale is important for understanding the role of molecular boundary films in cartilage tribology. However, the effect of the removal of boundary films and other proteins during sliding on the friction properties of cartilage has largely been ignored in macroscale friction studies. Although the presence of boundary films is an important factor in measuring friction at any scale (Jay et al., 2007; Gleghorn et al., 2009; Chan et al., 2010), continuous sliding of cartilage in macroscale friction tests removes not only molecularly thin boundary films, but also other proteins including collagen (Stachowiak et al., 1994; Gleghorn et al., 2010). Furthermore, in friction studies performed with microprobe-based instruments such as the atomic force microscope (AFM), the cartilage surface is not subjected continuously to normal and shear loading, whereas in macroscale studies traditionally performed with a tribometer, the cartilage surface is continuously

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