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Fluid movement and joint capsule strains due to flexion in rabbit knees

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ABSTRACT

Diarthrodial joints are freely moveable joints containing synovial fluid (SF) within a connective tissue joint capsule that allows for low-friction and low-wear articulation of the cartilaginous ends of long bones. Biomechanical cues from joint articulation regulate synoviocyte and cartilage biology via joint capsule strain, in turn altering the composition of SF. Joint flexion is clinically associated with pain in knees with arthritis and effusion, with the nociception possibly originating from joint capsule strain. The hypothesis of this study was that knee fluid volume distribution and joint capsule strain are altered with passive flexion in the rabbit model. The aims were to (a) determine the volume distribution of fluid in the joint at different total volumes and with flexion of rabbit knees *ex vivo*, (b) correlate the volume distribution for the *ex vivo* model to *in vivo* data, and (c) determine the strains at different locations in the joint capsule with flexion. During knee flexion, ~20% of anteriorly located joint fluid moved posteriorly, correlating well with the fluid motion observed in *in vivo* joints. Planar joint capsule principal strains were ~100% (tension) in the proximal–distal direction and ~−40% (shortening) in the circumferential direction, relative to the femur axis and 30° strain state. The joint capsule strains with flexion are consistent with the mechanics of the tendons and ligaments from which the capsule tissue is derived. The movement and mixing of SF volume with flexion determine the mechanical and biological fluid environment within the knee joint. Joint fluid movement and capsular strains affect synovial cell biology and likely modulate trans-synovial transport.

1. Introduction

Diarthrodial joints are freely moveable and contain synovial fluid (SF) within a connective tissue capsule that allows for low-friction and low-wear articulation. In the knee, the joint capsule (a.k.a. articular capsule or capsular ligament) is a thin, but strong and flexible fibrous membrane derived from the fascia lata, quadriceps tendon, and surrounding ligaments (Gray, 1918). The intra-articular face of the joint capsule is covered by the synovial membrane, which contains a highly fibrillar intimal matrix layer, synovium, that is densely populated with synoviocytes (McDonald and Levick, 1988; Simkin, 1991).

Biomechanical cues from joint articulation regulate synoviocyte biology, in turn altering the composition of SF. SF contains several lubricant molecules, including high molecular weight hyaluronan (HA) (Balazs, 1974; Dahl et al., 1985; Mazzucco et al., 2004) mainly secreted by synoviocytes (Smith and Ghosh, 1987). The secretion rate of HA by synoviocytes is mechanosensitive at the cellular (Momberger et al., 2005) and joint scale (Ingram et al., 2008). Despite the mechanosensitive nature of these tissues, the biomechanics of knee joint capsule *in situ* are largely unexplored.

The overall and local SF volumes are important physiological quantities, as the biological and biomechanical effects of SF are concentration-dependent, and joint effusions may alter such concentrations. SF exhibits a number of volume-dependent mechanobiological features, including modulation of tissue biology by providing cytokines and alteration of joint friction and wear biomechanics based on lubricant concentration (Schmidt et al., 2007). SF volume can be increased with therapeutic injections, in diseases such as osteoarthritis (OA), and after traumatic injury.

In addition to the basic science motivations for understanding synovial fluid movement and capsule strain during articulation, joint flexion is clinically associated with pain in knees with effusion, and the nociception possibly originates from joint capsule strain. Patients typically maintain knees with effusion at 30–60° flexion, with pain and intra-articular fluid pressure increasing during further flexion (Eyring and Murray, 1964; Jayson and Dixon, 1970). The nociception of such joint pain may originate in the capsule, as joint capsule strain has been correlated with afferent nerve impulses in an animal model (Lu et al.,

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