The Effect of Femoral Head Ischemia on Bone Strength, Microstructure and Failure Patterns

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INTRODUCTION:

Legg-Calvé-Perthes Disease (LCPD), a common pediatric hip disorder, can lead to permanent deformity of the femoral head and premature osteoarthritis [1-4]. LCPD is one form of juvenile ischemic osteonecrosis (IO). Previous studies have indicated that the vascular disruption results in increased bone resorption without a corresponding increase in bone formation, and also in altered mechanical properties of the articular cartilage and underlying epiphyseal bone [1-4]. However, the biomechanical mechanisms underlying these changes in mechanical properties have not been characterized.

The overall goal of this study was to assess the effect of IO on bone structure-function relationships and failure mechanisms in the femoral head. Specifically, the objectives were to: (1) compare the trabecular microstructure in IO vs. normal femoral heads; (2) determine the effect of IO on relationships between mechanical properties and trabecular microstructure; and (3) characterize differences in failure mechanisms between IO and normal femoral heads.

METHODS:

Specimen Preparation. IO was surgically induced in the right femur of six male piglets aged six to eight weeks old, as described previously [4]. Both left and right hip joints were harvested two weeks post surgery. Three pairs of matching osteochondral cores of square cross-section (~4x4 mm²) were machined from a central coronal section. One pair was medial to the ligamentum teres insertion and two pairs were on the lateral side [4]. Tissues were kept frozen throughout processing and when not in use. µCT Imaging. Coronal cores from the femoral head were scanned at a resolution of 12 µm/voxel (µCT 40, Scanco Medical, Brüttisellen, Switzerland). Trabecular architecture was analyzed for a volume of interest (VOI) that extended from ~300 µm distal to the calcified cartilage to ~300 µm proximal to the physis. Mechanical Testing. Cores were prepared for mechanical testing by potting the bone end of each core in polymethyl methacrylate while maintaining core alignment. The samples were then sprayed with enamel paint to enhance image contrast (Figure 1). After preconditioning, the cores were loaded in compression to 50% strain at a rate of 0.5% sec⁻¹ (Instron 8874, Instron, Canton, MA). Digital images (10 µm/pixel) were captured at ~0.3 Hz throughout the test and were used to quantify the strain induced in only the bone of the femoral head. The elastic modulus, yield stress and ultimate stress of the femoral bone cores were computed from the resulting stress-strain curve. Analyses of Failure Patterns. The series of digital images were analyzed using custom digital image correlation technique [5] in order to determine the patterns of deformation throughout the femoral and acetabular cores. Statistics. Repeated measures analyses of variance (ANOVAs, JMP 6.0, SAS Institute Inc., Cary, NC) were used to determine the dependence of microstructural and mechanical properties on treatment (IO vs. normal). These analyses accounted for inclusion of multiple cores from each femoral head.

RESULTS:

IO significantly affected the microstructure of the epiphyseal trabecular bone (p<0.05, Figure 2A). Bone specimens from the IO femoral heads displayed decreased volume fraction (Vf), tissue mineral density, trabecular thickness (T.b.Th*), trabecular separation (T.b.Sp*), and degree of anisotropy, and increased trabecular number (T.b.N*), structural model index (SMI), and connectivity density. IO also resulted in a markedly decreased Young’s modulus (p=0.004, Figure 2A); however, no effect of IO on the relationship between modulus and microstructural properties such as Vf and SMI was found (p>0.08, Figure 2B). The differences in yield stress were found between IO and normal femoral bone, most likely because of the frequency of the digital image capture was too low to provide sufficient precision in detecting the yield point.

Analyses of failure patterns indicated that for normal femoral cores, large, localized deformations occurred in the superficial zone of the cartilage and within the calcified cartilage (Figure 3). For IO femoral cores, however, large deformations occurred throughout the cartilage layer and underlying femoral bone. Overall, strains in the femoral bone were higher in the IO cores as compared to normal cores.

DISCUSSION:

Ischemic osteonecrosis substantially altered the trabecular microstructure in the epiphyseal bone of the femoral head, resulting in a more porous, isotropic, well-connected structure with thinner, less sparsely spaced and more rod-like trabeculae. IO also resulted in decreased tissue mineral density, suggesting that the mechanical properties of the trabecular tissue may be affected. Consistent with previous findings [4], the modulus of the femoral bone was reduced with IO, and the present results indicate that this reduction is directly linked to the alterations in microstructure. Perhaps as a consequence of the changes in modulus and tissue mineral density, the strains sustained by the femoral bone were higher with IO. Moreover, with IO, high strains occurred throughout the depths of the femoral cartilage and femoral bone, as opposed to being localized at the articulating surface and calcified cartilage. Taken together, these findings indicate that IO induces changes in mineralization and microstructure in the femoral head and that these changes result in distinct differences in the way that loads applied at the hip joint are distributed throughout the articulating cartilage and underlying bone.

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