INTRODUCTION:
Focal cartilage defects are very common and widespread disorders that result from traumatic injuries or imbalanced joint loading. Early detection and repair of these defects could prevent the onset of osteoarthritis and its associated burdens. One promising repair strategy is the implantation of chondral and osteochondral tissue engineered (TE) constructs. Determination of the stress and strain distributions that the constructs experience when implanted is critically important to their function and efficacy. Additionally, successful TE repair strategies require integration of the implant with the native tissue. The relative displacement between TE construct and native articular cartilage (AC) at their interface can disrupt molecular bridges and early integration of the engineered and native tissues. However, it is not known whether implant material properties affect this integrative cartilage repair [1]. To address these issues, finite element (FE) models of engineered chondral tissue with integration at the bottom surface (i.e. an osteochondral implant fully integrated to bone) in the human tibiofemoral joint, including geometric and material property discontinuities at the engineered/native cartilage interface, are presented.

METHODS:
The femur was modeled as a rigid impermeable indenter while the fluid and solid phase interactions and fixed charge densities (FCD) in tibia/AC were represented with four-node bilinear displacement pore pressure elements in a biphasic swelling model (ABAQUS® 6.6). Biphasic swelling is a simplification of triphasic and quadruphasic models in which the effect of FCD is represented as a swelling pressure [2,3]. Four axisymmetric models for the following cases were developed: (A) a TE construct with identical properties to AC and fully integrated with native tissue (i.e. intact joint or continuous-homogenous case), (B) a TE construct with lower proteoglycan (PG) content and stiffness compared to AC and fully integrated with native tissue (continuous-inhomogenous), (C) TE construct with identical properties to AC but no integration with native tissue (discontinuous-homogenous), (D) TE construct with lower PG content and stiffness compared to AC and no integration with native tissue (discontinuous-inhomogenous). The femoral indenter was 30mm in radius, and the tibial AC was 80mm in radius and 2.1mm thick [4]. Full integration in cases (A) and (B) was represented by modeling transplant and native AC as a continuous geometry. In (C) and (D) where the TE construct and native AC were not integrated, the two tissues were modeled as separate geometries and frictionless contact between the two was defined.

In order to model transplanted TE construct with lower PG content and stiffness, a 2.5mm region with 15% less FCD and 65% lower stiffness compared to native AC was created in the center (Fig 1). In models where the bottom surface was impermeable, and zero pore pressure was prescribed on the upper surface. The displacements of the nodes on the bottom plane were confined in all directions representing cartilage attachment to the tidemark/bone. The solid collagen-PG matrix was modeled as a Neo-Hookean material with properties comparable to those from the literature; strain-dependent permeability was defined [2]. Osmotic swelling pressure and chemical expansion stress were included in the model in a UMAT subroutine. Stress relaxation response of the sample was investigated by applying a 10% strain to the AC over 0.5 sec, and then holding it constant for 5000s. During 0.5 sec loading step, relative vertical displacement between adjacent nodes on TE construct and native AC at six different locations through the height were calculated and compared for cases (C) and (D).

RESULTS:
Large differences in mechanical field variable distributions including stress, strain and pore pressure were observed between different cases. Transplants with lower stiffness and PG content experience lower stress (Fig 2B, 2D). The transplant with inferior properties introduced severe discontinuity of the stress distribution, even when fully integrated with native AC (Fig 2B). Similarly, lack of integration introduces a discontinuity in stress distribution even in case of ideal transplant properties (Fig. 2C). Comparing the results for relative vertical displacement between discontinuous-homogenous and discontinuous-inhomogenous cases (C and D) at the six different locations on transplant/native AC interface showed less than 10% difference. For both cases (C) and (D), the highest relative vertical displacement was calculated to be at location 4, slightly below the mid-depth of sample (Fig 3, case (D) not shown).

DISCUSSION:
Simulations were performed to investigate the effects of geometry and material property discontinuities on distribution of various mechanical field variables in a chondral TE implant. Lower stiffness and PG content of the transplant greatly influence the stress, strain and pore pressure fields which could affect biological response of implanted cells. It was also observed that lack of integration introduces slight stress discontinuity at the transplant/AC boundary. The transplant with inferior properties introduced severe discontinuity of the stress distribution, even when it was fully integrated with native AC. These results confirm those obtained by Wu et al. [5].

A challenge with any engineered cartilage application is the integration of the implant into the surrounding native tissue. Relative displacement between the engineered and native AC could interfere with initiation of integration and formation of molecular bridges. To investigate the effect of implant material properties on integrative repair response, relative vertical displacement at implant/AC boundary were calculated at various depths. Our results did not show a substantial difference in relative vertical displacement between cases (C) and (D) which suggests that an implant with inferior properties does not disrupt the integrative repair process anymore than an ideal implant. Finally, the present simulations may be helpful in future designs and evaluations of osteochondral TE strategies and implantation techniques.

REFERENCES:

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