INTRODUCTION
Experimental knee simulators for in vitro testing provide valuable insight into the mechanics of the natural and implanted joint; previous studies have investigated the effects of total knee replacement (TKR) design and surgical alignment on joint kinematics, contact mechanics, or soft-tissue loads. However, the number and type of in vitro tests which can feasibly be performed is limited by the need to make physical implant parts and the substantial time required to carry out each test. Computational simulations provide a complementary tool to in vitro testing; experimental data can be used to validate the computational model which can subsequently be used in a design-phase timeline to evaluate the influence of component design, alignment, or loading conditions.

Prior work has developed a finite element (FE) model of the Kansas knee simulator (KKS), which is a dynamic, five-axis simulator designed to apply physiological loading across the knee for a variety of activities [1]. Model-predicted joint kinematics and loading have been previously validated during force-controlled gait and deep flexion activities [2,3]. The objective of the current study was to interface a proportional-integral-derivative (PID) controller with the FE knee simulator such that control of both the experiment and computational model is accomplished in the same way. Subsequently, the model was applied to evaluate the effects of TKR design and over- and under-stuffing of the patellar button on required quadriceps force during a simulated deep knee bend.

METHODS
A dynamic FE model of the KKS was previously developed in Abaqus/Explicit (Simulia, Providence, RI) [2]. In this prior model, the quadriceps actuator was force-controlled using a loading profile experimentally measured from the KKS. However, the experimental simulator operates the quadriceps in displacement control in order to match a desired knee flexion angle, and monitors the required quad force. Hence, a feedback control system was implemented within an Abaqus/Explicit user subroutine to control the quadriceps in the same manner as the experiment. Instantaneous hip flexion angle, measured from the model, was fed into the PID controller subroutine to calculate the instantaneous quadriceps displacement required to match a target flexion profile (Figure 1).

The control system was evaluated during a deep knee bend activity for a series of analyses. Subject-specific natural and implanted models were developed and the effect of TKR on quadriceps force was evaluated (Figure 2). An implanted knee, with a patellar button initially aligned in the neutral position, was over- and under-stuffed by 5 mm and 2 mm, respectively, in order to quantify the effect of composite patellar thickness on quadriceps forces. This analysis was performed using both dome-compatible and anatomic component designs (Figure 3).

RESULTS
The PID-controlled FE model consistently reproduced the target flexion profile across all analyses (Figure 1). RMS differences were < 1.5º between target and analyses, and < 0.3º between analyses. Comparing natural and implanted conditions, TKR reduced peak quadriceps force by 20% (Figure 2).

Overstuffing reduced quadriceps force by 10% in both TKR designs at low flexion angles (< 50º), but differences became negligible in deeper flexion. The dome-compatible design generated substantially lower quadriceps force in deeper flexion than the anatomic; peak force was 20% lower in the dome design. Kinematics differences of 6º and 3mm were observed in patellar internal-external (I-E) rotation and medial-lateral (M-L) translation, respectively (Figure 3).

DISCUSSION
The PID-controlled computational knee simulator adapts to changes in component geometry, size and alignment to match the desired activity flexion profile, providing control of the model in the same manner as the experimental setup.

Differences between natural and implanted cases showed similar trends to experimental measurements by D’Lima et al. [4], with higher quadriceps force in the natural knee in deeper flexion. This change is multifactorial, likely attributed to the amount of femoral roll back and small increase in size with the implant creating a larger effective moment arm in deep flexion.

Over- and under-stuffing of the patella demonstrated similar results between the two designs; at low flexion angles the overstuffed patella reduced the quadriceps force required, however, once the extensor mechanism contacted the femoral component the quadriceps force was similar for each composite thickness.

Substantial differences were measured in deep flexion between the dome and anatomic designs. Articular geometry and less patellofemoral constraint with the dome appear to allow an improved relative position for quadriceps efficiency in this simulator.

The PID-controlled FE model can be applied to assess quadriceps force across different specimens, the effects of component alignment and design, and provide insight into the mechanisms controlling quadriceps force before and after TKR.

REFERENCES

Figure 1: Computational model of the Kansas knee simulator with a TKA specimen (left); Target and achieved hip flexion profiles for natural and implanted analysis (right)

Figure 2: Natural (left) and implanted (center) specimens in the KKS model; quadriceps forces predicted by the model (right)

Figure 3: Effect of component design (top left) and over- and under-stuffing of the patella on quadriceps force (top right); patellar kinematics for anatomic and domed components (bottom)

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