Introduction: Total knee replacement (TKR) has long been considered the gold-standard procedure for knees badly damaged by osteoarthritis and other bone and cartilage degenerating diseases. It is estimated that by the year 2030, primary TKR procedures will reach frequencies of 3.5 million per year in the United States alone [1]. Unfortunately, wear particles of the ultra high molecular weight polyethylene (UHMWPE) insert are known to trigger a negative tissue reaction in the surrounding bone called osteolysis [2](active resorption or dissolution of bone tissue). TKR wear performance can be evaluated experimentally using standardized testing, such as the load and displacement waveforms outlined in ISO 14243-1 [3]. However, testing protocol often requires a variety of expensive equipment, supplies, trained personnel, as well as the prototypes which are destroyed through the testing. For these reasons, the use of computational or in-silico testing methods has gained popularity. The use of implicit and explicit finite element (FE) models have found applications in this field. A simulation has been developed which uses implicit FE contact analysis for the simulation of ISO 14243-1, with wear predictions based on Archard’s wear model [4], as well as creep and cross-shear. This abstract outlines validation work using resultant forces, volumetric wear and wear damage patterns to refine and support this model.

Materials and Methods: Wear testing is performed using an AMTI Force 5 displacement controlled wear simulator. For TKR testing, this machine features displacement control for flexion–extension and anterior–posterior (AP) displacement of the femoral component, internal-external (IE) rotation of the tibial component, and force controlled axial load applied through the tibial component. Rotation of the tibial component about the AP axis as well as displacement along the medial-lateral (ML) axis is left unconstrained. ISO 14243-1 is a set of load and displacement waveforms for force controlled wear simulators, where the femoral AP and tibial IE rotation degrees of freedom have forces applied (rather than prescribed displacements) and added resistance is supplied using springs. In order to use these standards on a displacement control machine, it is necessary to perform a preliminary simulation of a force controlled tester. FE meshes of a Depuy Sigma PCR TKR femoral component and UHMWPE insert are generated, which are suitable for implicit FE contact analysis. We apply the loads and boundary conditions as specified in the standard, including the resistance of a 30 N/mm restraint against AP displacement, and a 0.6 Nm/degree restraint against IE rotation. Following simulation, the displacement data is used as input for the displacement controlled wear tester. Displacement waveforms are tested on the Force 5 and modified/smoothened if necessary, and the resulting waveforms are used for both experiment and simulation. Resultant forces are measured by a load cell located in the tibial component of the wear tester, and recorded for several cycles during different instances throughout the test. A fluid handling system keeps implant components immersed in a bovine serum solution maintained at 37°C. The wear tester is stopped every 500,000 cycles for cleaning, to replace the bovine serum solution, weigh the test specimen and record surface damage with a laser scanner. This process is repeated for up to 3.5 million cycles. Gravimetrically measured wear rates and surface damage are compared to simulation results, where empirical factors are selected to better match experimental results.

Results: A comparison between resultant forces calculated in the FE simulation and those recorded from the load cell in the tibial component of the wear tester showed very good agreement, with the exception of forces measured in the ML direction and moments about the AP axis of the tibial component. The wear history for the UHMWPE insert as measured gravimetrically is shown in figure 1 below. The change in mass represents the decrease in the mass of the UHMWPE, corrected for protein absorption measured using an unloaded soak control. Simulation predicted wear rates are shown for comparison.

Figure 1 Comparison of measured wear rates (blue) versus simulation predicted wear rates (pink).

Surface scans of the UHMWPE insert were processed using the Innovotech Polyworks software suite, where comparisons between worn and unworn scans can be plotted. The wear plot after 3.5 million cycles is shown below, in comparison to the simulation predicted damage pattern after the same number of cycles.

Figure 2 Comparison of measured damage distribution (left) versus simulation predicted damage distribution (right), after 3.5 million wear cycles.

Discussion: Comparing resultant forces measured experimentally with those calculated through simulation, disagreement is seen in some degrees of freedom. These deviations are most likely due to limitations in the FE model, where displacement along the ML axis and rotation about the AP axis are assumed to be perfectly frictionless. In-vitro, friction does appear to play a role and small forces and torques are generated in these directions. While trends in wear rates and the shape of the damage patterns show good agreement, depths clearly differ. This is due to the fact that the damage pattern is the result of wear and creep. Simulated creep magnitudes are low, since the damage depths are lower despite wear rates being similar. Further work will include a validation phase where perturbed loading conditions will be used. The model will be verified when simulation results can match experiment results while both undergo the same perturbations in load, without changing any empirical factors. Future work will also include the consideration of friction at the tibial support.