INTRODUCTION:
Total knee replacement (TKR) has a long clinical tradition in orthopedic arthroplasty. To ensure not only pain reduction but also a restored joint function when performing a TKR for patients with arthritis, prostheses need to be designed and developed according to anatomical and functional biomechanical requirements. Additionally, mechanical integrity and appropriate balancing of the ligaments are essential for successful TKR outcomes. The application of computer models is a common method for supporting design of prostheses through prediction of function. In addition to enabling exploration of kinematics and kinetics specific to the joint of a single specimen, reflecting both joint surface topology and soft tissue properties, this method allows interrogation of different design parameters within a short time compared to experimental evaluation. Specimen specific joint laxity and its influence on kinematics and kinetics following TKR can be analyzed.

The objective of this study was to develop and validate specimen specific computer models suitable for predicting knee joint kinematics as well as laxities of the reconstructed knee. Validation was achieved by comparing the predicted knee joint kinematics of clinical laxity tests after TKR against results obtained from robot experimental tests.

MATERIALS AND METHODS:
In-vitro experiments on six human post-mortem knee specimens were performed using a 6 degree of freedom (DOF) industrial robot (KUKA, Augsburg, Germany). The robot was equipped with a 6 DOF force-torque sensor (ATI, Apex, NC). Passive kinematics, laxities under low (44N) and high (500N) compressive loads, as well as the kinematics and forces of functional activities (lunge, knee bending, level walking, stairs up, stairs down) were determined. Data for the intact knee joint, as well as of the knee with implanted TKR, were obtained. The implantation was performed by a well qualified surgeon. Force controlled laxity testing consisting of varus-valgus (VV) rotation, internal-external (IE) rotation, anterior-posterior (AP) translation, medial-lateral (ML) and proximal-distal (PD) translation of the intact and implanted state were performed while measuring the kinematics of the specimen. Two different types of prosthesis design were implanted in three specimens: a contemporary posterior cruciate retaining (CR) design, and a contemporary posterior stabilized (PS) design. The implant positions were derived using an optical tracking system (Optotrak, Northern Digital Inc. Waterloo, Ontario). After testing, the properties of passive soft tissue structures were investigated by performing a resection study using a stepwise resection of the posterior cruciate ligament (if present, depending on type of implant), medial collateral ligament, lateral collateral ligament, popliteus tendon, and capsule. For each resection state the kinematics of the intact state were “played-back” using the robot to measure the kinetic response of the remaining soft tissue structures.

For each tested specimen, a specimen specific computer model was created. A model consisted of the 3D geometry of the femur, tibia and fibula bones including the joint cartilage based on CT and MRI scans. The specimen specific passive soft tissue properties as determined during the in-vitro robot experiments were incorporated using a phenomenological ligament model that was calibrated using the experimental data from the resection study.

For each specimen specific computer model a virtual TKR surgery was performed using the same prostheses type, size and positioning parameters, as performed during experiments. The prosthetic components and the bones where modeled as rigid bodies with an appropriate contact definition between the femoral component and the tibia insert [1]. The femur bone of the computer model of the knee joint was driven by force and moment control in 5 DOF, consistent with the experimental protocol, while the flexion was displacement driven. The tibia bone was constrained. Finite element analyses (FEA) of all six implanted specimen specific models were performed using Abaqus/Explicit (SIMULIA, RI). Consistent with the experiments, the VV, IE, AP and ML laxity tests were analyzed at 5 different flexion angles starting with 12°, followed by 30° increments from 30° to 120° flexion.

Validation of the specimen specific implanted computer models against the in-vitro robot experiments was performed by comparing the resulting kinematics of the laxity tests. Kinematics were quantified as the projection of the femur flexion facet centers (FFC) [2] of the femoral condyles onto the tibia, and were predicted for the intact and implanted states. From among all samples and test conditions considered, a subset is shown here as representative of the model validation. In particular, one specimen with an implanted PS design was chosen as representative. Additionally, as the VV laxity test reflects the balancing of the collateral ligaments achieved during TKR, this laxity test was selected from among the full set of laxity tests for assessing model validation.

RESULTS:
The resulting extreme points (FFC end positions of the force/moment controlled laxity test) measured for the VV laxity test are presented in Figure 1, from both the experimental tests and the model predictions. The proximal positions of the medial and lateral FFC as a function of flexion angle are shown, with differences of equal or less than 1.1mm (3.4 %) between the model and experiment.

DISCUSSION:
Based on the VV laxity test, proximal positions of the medial and lateral FFCs predicted for the implanted computer model matched closely the robot proximal positions. The deviations between the computer model and robot experiment, for the examined flexion angles, ranged between 0.4 mm and 1.1 mm. The largest deviation of the FFC proximal position between the computer model and the robot (1.1 mm) occurred at a flexion angle of 120° for the FFC of the lateral condyle. The lowest deviation between model and robot (0.4 mm) was found for flexions of 30° and 90° for the lateral FFC.

In general the computer model tended to predict a slightly more lax response, especially for the medial condyle, than measured experimentally. However, the overall trends of the computer model data matched the trends of the robot VV laxity data.

Based on the results shown here, the specimen specific computer model is considered validated within an accuracy of 1.1 mm. Results from all six specimens and for both laxity and functional loading will be presented.

SIGNIFICANCE:
Validated and calibrated specimen specific numerical knee models afford the possibility to accurately investigate the effect of implant placement and ligament balancing on joint kinematics and kinetics. The specimen specific model presented here is shown to predict passive kinematics as well as joint laxities, and thus provides an efficient and accurate testbed for assessing TKR performance.

REFERENCES