

Appendix A: Supplementary data

A robotic knee simulator was used for the validation of the numerical TKA model. The knee simulator was designed based on a main hydraulic load unit (MTS Bionix, USA) and additional prismatic actuators (Custom Actuator, MN, USA)(Arami et al., 2015). The simulator included parts replicating the femur, tibia, patella, and quadriceps muscle (Figure 1). The same ultra-congruent mobile-bearing knee prosthesis was inserted into the simulator. The hip was attached to a load unit and could rotate and translate in the sagittal plane. The ankle was attached to the ground and could only rotate in the sagittal plane. The hip and the ankle were aligned. A smaller actuator was attached to the femoral part and replicated the quadriceps force. The quadriceps and patellar tendons were represented as a solid webbing strap attached to the patella and linking the quadriceps actuator and the tibia. The system was controlled by MTS FlexTest60 software (MTS, USA), which provided control, data acquisition, and multi-axial testing precision.

The knee simulator performed a loaded (half bodyweight = 300 N) squat movement from 10 to 60 degrees of flexion. The knee flexion was controlled by the quadriceps and hip forces. For each angle of flexion, a constant load was applied on the hip. The simulator searched for equilibrium by keeping constant axial reaction force in the ankle (300 N) through a control of the quadriceps actuator force with help of an adapted self-learning algorithm (Arami et al., 2008; Lucas et al., 2004).

The quadriceps muscle force and ankle reaction force were measured by the force sensors. The patellar kinematics was measured via a motion capture system (Vicon, UK) and 18 reflective markers (8 on the femur, 6 on the tibia and 4 on the patella).

During the simulated movement, the position of the markers, as well as force values were recorded after the system reached equilibrium at the set angle. Measurements were done every 5 degrees of the knee flexion. At least 1000 frames per angle were used to record a position of markers. The experiment was repeated 5 times. Average and standard deviation (SD) were evaluated at these static positions. The experimental error of measurements was defined as 1.96 SD (95% confidence interval).

The validation of the TKA joint model against a robotic simulator required several adaptations of the numerical model. The 4 quadriceps muscles were replaced by a single muscle, modeled by two parallel connector elements. The geometry and position of all components in the numerical model were adapted to the robotic simulator. The quadriceps and patellar tendons were modeled by two linear springs ($E = 100 \text{ MPa}$, $\nu = 0.3$, $\text{CSA} = 54 \text{ mm}^2$). The mechanical properties were estimated with tension test. We simulated a loaded (half bodyweight = 300 N) squat movement from 10 to 60 degrees of knee flexion.

The differences between the measured and predicted translations and rotations of the patella and quadriceps force were evaluated with a root mean square error (RMSE).

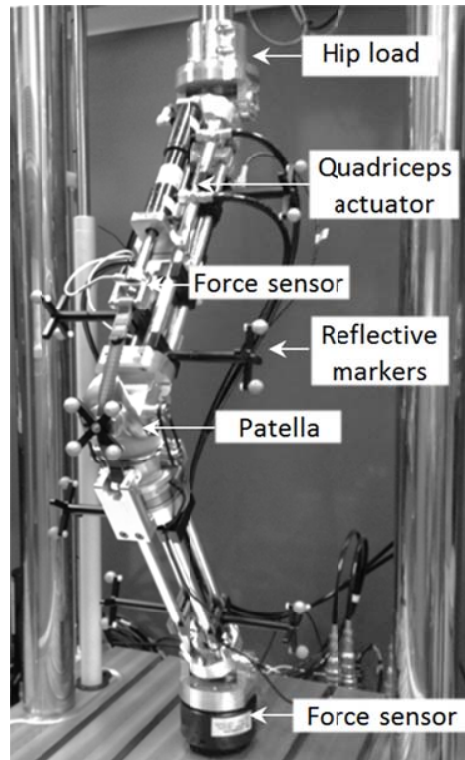


Figure 1. Robotic knee simulator.

References

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