The Variation of Active Knee Kinematics Is Encompassed by the Passive Envelope of Motion

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Introduction:
Knee stiffness and unnatural feeling knees were identified as two main determinants of patient dissatisfaction after total knee arthroplasty (TKA) [1]. Therefore, it is important to understand the range of motion occurring in every day knee activities in order to design knee implants that restore the natural knee stability. However, active knee joint kinematics differs between the various types of activities [2, 3], individuals [2], and foot positions [4]. Hence, the test development for each activity and the execution of measurements become complex and time-consuming tasks. Passive knee laxity also varies between individuals but the necessary tests are less extensive and can be run in-vitro without any assumptions regarding muscle forces. The resulting envelopes of motion, introduced by Blankevoort et al. (1988) [5], describe the limits of passive knee joint kinematics. It was assumed that these passive limits protect the knee against damage and thus should also be valid in active situations. Therefore it was hypothesized that the active knee kinematics are encompassed by the passive knee joint envelope of motion.

Methods:
After CT and MRI scanning for registration purposes, seven human leg specimens (Science Care, Phoenix, Arizona, USA; permission obtained from the local ethics commission) were prepared by dissecting the foot and femoral head and cementing the bony ends into fixtures. Another CT scan of each potted specimen was taken before a contemporary TKA design was implanted by an orthopedic surgeon. All tests were performed on a six degree-of-freedom (DOF) industrial robot (KUKA, Augsburg, Germany) with a six DOF force-torque sensor (ATI, Apex, NC, USA) attached to the end of the robot arm. The tibia was fixed to the sensor and the femur to a pedestal. Based on the scans, individual anatomic femoral and tibial coordinate systems (CS) were determined. Via the fixtures and the CT scans of the potted specimens, the anatomic CS were calculated with respect to the robot CS. Then, force-torque-controlled anterior-posterior (AP, +/-100 N), medial-lateral (+/- 100 N), and internal-external (+/- 6 Nm) laxity tests, each with 44 N and 500 N compression and at ten different flexion angles, were applied in the tibial CS while recording the relative kinematics and kinetics. Furthermore, the motions during activities of daily living (level walking, stair ascent, stair descent, and knee bend) were simulated on the robot by applying forces and moments based on those collected in vivo with instrumented tibias [6]. All data analyses were conducted with Matlab (R2013b, The MathWorks). For the creation of specimen-specific envelope borders, the maximum AP displacements of the medial and lateral center of the posterior condyles (CPC) with respect to the tibial CS were calculated from the combined laxity test data and combined activity data. The resulting borders were averaged over all specimens.

Results:
The average AP activity envelope lies within the average passive envelope of laxities measured at 44 N and 500 N compression (Figure 1). This is also true for the comparison between the specimen-specific AP active and passive envelopes of the medial and lateral CPC. The width of the average AP activity envelope ranges from 1.0 mm (close to 100 degree flexion) to 6.1 mm (close to 50 degree flexion) for the medial CPC and from 1.2 mm (close to 100 degree flexion) to 6.8 mm (about 60 degree flexion) for the lateral CPC. In terms of the individual data, the AP activity envelope of the medial CPC encompasses up to 48% of the 44 N laxity envelope and up to 58% of the 500 N laxity envelope. The lateral CPC AP translations of the individual specimens during activities reach a maximum of 74% of the 44 N and 75% of the 500 N envelope. In general, the activity envelope tends to be closer to the laxity envelope measured with 500 N compression compared to the laxity envelope with 44 N compression. The shape of the activity envelope tends to follow the shape of the laxity envelope (Figure 1 and 2): If the laxity envelope increases or curves, the activity envelope increases or curves as well. The individual activity plots demonstrate that each activity has its own unique knee motion path (Figure 2). Furthermore, the activity kinematics also differs between specimens.
Figure 1: Average AP passive envelopes of 44 N and 500 N compression laxity tests as well as average activity envelope; both measured in the medial (left) and lateral CPC (right).

Figure 2: AP passive envelopes and four activities measured in the lateral CPC with one specimen.

Discussion:
The results show that after TKA the AP activity envelope is encompassed by the passive AP envelope of motion, in particular the envelope at 500 N compression. The reason for the better approximation of the activity envelope by the 500 N compression envelope is that the average compressive force during the various activities was closer to 500 N than 44 N. It is possible that if the shear-to-compressive force ratio from the activity force profile was applied during the laxity testing, an even closer match of the active and passive envelope could be achieved. This was not part of the present study but should be investigated in the future.

To the current knowledge of the author, no study has reported laxity and activity tests performed on the same specimens. The present results agree with the previously reported finding that activity kinematics vary depending on type and individual [2, 3]. A limitation of the performed activity tests is that the applied forces and moments result from an ultra-congruent design, which differs from the less congruent designs used in the present study. It is assumed that with a less congruent design, lower in-vivo forces and moments would have been obtained and thus possibly narrower activity envelopes measured in the robotic activity simulation. However, it is believed that the main conclusion would not have been altered.

Significance:
In order to design a TKA that satisfies the patient’s needs, one important factor is to consider the activity envelope. The measurement of activities, however, is complex. The results of the present study showed that the activity envelope of motion can be approximated by the passive laxity envelope.

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References: