A New Design Concept for a Surface-Guided Total Knee Replacement with Normal Kinematics

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INTRODUCTION:
The differences in the functional outcomes of the subjects with normal knees and those who have undergone TKR may be related to different kinematics between the normal and the artificial knees (Victor and Bellemans, 2006; Andriacchi T.P and Dyrby C.O, 2005). To design for a TKR with normal kinematics, a concept for a surface-guided TKR with converged femoral condyle has been proposed in the literature (Walker, 2001); the especially-shaped bearing surfaces, in particular the converged lateral femoral condyle, were suggested as the design feature for controlling the motion of the joint. Combinations of ramp features and an anterior recess/pad have also been suggested as potential designs for producing normal kinematics (Walker et al., 2007).

In this study a novel design concept for a TKR with normal kinematics was introduced and tested. The novelty of the design is in the shapes of the lateral bearing surfaces that can actively control the axial rotation of the joint in both directions during the full cycle of extension and flexion. The shape of the medial compartment in this design, similar to medial pivot knees, is congruent and it replicates a ball-and-socket articulation. To test the viability of the design, prototypes of the components with the suggested shapes were made and their kinematics under the effect of compressive loads were tested experimentally.

METHODS:
The shape of the lateral bearing surface of the femur was defined by a series of 2D curves on the frontal plane at equal intervals of flexion angle from 0° to 150°. In the design of the lateral condyle, the bearing spacing between the condyles was assumed constant, and the shapes of the lateral contact curve was composed of two circular tangent arcs on the medial and lateral sides of the contact point, radii of which varied in opposite directions by increase and decrease of flexion (Figure 1-A). The shape of the matching tibial bearing surface was formed by moving the femur over the top of the tibia (following the desired kinematics), with continuous removal of the volumes of the intersecting materials from the tibial block (Walker, 2001). The passive kinematics of a cadaver knee, after being processed to meet the required kinematics characteristics for this particular design, was used as input for generating the shapes of the bearing surfaces.

Figure 1 – Suggested design features for (A) lateral and (B) medial compartments. A: The design features of the contact arc on the lateral condyle include constant bearing spacing and different radii of curvature on the medial and lateral aspects of the contact arc. B: The medial femoral condyle has three features: the posterior spherical facet (PSF), the anterior stabilizing facet (ASF), and the natural patellar groove labeled in the figure 1, 2, and 3, respectively.

The optimum location of the medial ball-and-socket was determined from analysis of the passive motion of a representative cadaver specimen over the range of motion from 0° to 150° flexion, using Matlab programming language (Mathworks Inc, MA) and least square optimization routines. The shape of the medial femoral condyle included three geometric features as has been described in Figure 1-B. The shapes of these features were defined parametrically and optimized for maximum stability and minimum deviation from the anatomic shape of the articular surfaces of the femur. The shapes of the bearing surfaces and the design features of the tibial and femoral articulation have been illustrated in Figure 2. The suggested shapes of the bearing surfaces allow for preservation of the anatomic surface of the trochlear groove and normal tracking of the patella throughout the full range of motion. This design configuration also allows for options of preserving one or both of the cruciates to enhance motion control and stability. Rapid prototypes of the components were made from ABS material and put on an AMTI knee simulator equipped with an additional module that allowed for free motion and rotation of the tibial component in response to the guiding effect of the articular surfaces. Optotrak motion tracking LEDs were attached to the components, and compressive forces of 80lb, 115lb, and 160lb were applied on the joint.

RESULTS:
Figure 3 shows the relative motion of the femur with respect to the tibia for the tested range of motion. The results showed that the prototype generated a motion pattern very close to what was used as input for the design. The centre of the medial ball-and-socket and the lateral epicondyle showed translations and rotations of 0.9mm and 21° in comparison to 0mm and 22° values of the input kinematics.

Figure 3 – Comparison between the motion generated by the prototype and the kinematics that was considered as input for the design. The relative motion of the femur with respect to the tibia is illustrated by the relative location of the line that connected the centre of the medial ball-and-socket to the lateral epicondyle.

DISCUSSION:
The results of the tests validated the viability of the concept and methodologies for design of a surface guided knee. A design that can replicate the passive motion of the joint and the neutral path of motion around it can, in theory, generate normal kinematics in activities (Walker, 2001). The generated motion matched the kinematics observed for an unloaded knee joint. Appropriate laxities around the observed path can be obtained by adding adequate clearances to these bearing surfaces. The concept, design features, and methodologies developed in this study can potentially be used as the foundation for development of a new type of TKR with more normal kinematics.