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Application of a novel design method for knee replacements to achieve normal mechanics

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Purpose: The purpose of this study was to utilize a novel method for the design of total knee replacements for use in the absence of the cruciate ligaments, with the design criteria of reproducing the medial stability and lateral mobility characteristics of the normal anatomic knee.
Scope: The starting point was a femoral component with surfaces approximating anatomic. This surface was moved into multiple positions describing a neutral path of motion and laxity about the neutral path. The distal part of the femoral composite was then used to define the tibial surface. By varying the femoral design, different tibial surfaces were produced. The reference design featured a dished medial tibial surface and a shallow lateral tibial surface, but this provided limited motion guidance. To provide further guidance, two types of design were generated, one using intercondylar guide surfaces, the other providing guidance from the condylar surfaces themselves.
Conclusions: The design method was capable of generating a range of total knee surfaces which could potentially return the arthritic knee to more normal function.

1. Introduction

The first condylar replacement type of total knee replacement (TKR) for cruciate resection was the Freeman–Swanson [1], designed in the late 1960s. This used a roller-in-trough geometry which provided stability and a large contact area to minimize wear. The total condylar knee was designed with partially conforming bearing surfaces in the frontal and sagittal planes [2,3] to provide similar laxity and stability characteristics to the anatomic knee. The kinematic stabilizer and Insall–Burstein designs added an intercondylar cam-post mechanism to prevent anterior femoral subluxation and provide posterior femoral displacement in high flexion [4,5]. Such 'posterior stabilized' (PS) designs are now widely used but most have similar geometry for the lateral and medial condyles providing no lateral or medial bias to the motion.

More recently, designs have been produced which provide greater medial than lateral constraint. The medial pivot used a ball-in-socket for the medial compartment, and surfaces of low constraint on the lateral side [6,7]. The Journey knee [8,9], had a more constrained tibial medial side, a shallow lateral side, and a cam-post, resulting in more posterior femoral displacement laterally. Other design concepts have been proposed for a guided medial pivot [10], variable condylar contours [11] and an optimization approach based on constraint and maximum flexion [12]. All of these designs were intended to achieve more normal kinematics, a goal that is receiving increasing attention today, especially for more active patients.

To produce an optimal design, various mechanical criteria need to be satisfied as reported in numerous studies on knee specimens and on the living knee, in a wide range of test conditions and activities [13–24]. In the present study, to formulate design criteria which can be applied to TKR design, the term 'normal mechanics' will be used to focus on specific mechanical characteristics which are likely to affect the function in the patient. In previous studies, we described a preliminary method for the design of 'guided motion knees' and showed that motion characteristics resembling normal anatomic could be achieved in certain tests [24,25]. An advancement of this previous method is described in the present paper.

The major purpose of this study was to utilize a novel methodology for designing the bearing surfaces of guided motion TKRs to achieve the goal of 'normal mechanics', where this is achieved by the condylar surfaces together with intercondylar interaction, or by interaction of the condylar bearing surfaces alone.

2. Design method

2.1. Basic femoral bearing surfaces

The software (Rhinoceros 4.0, Robert McNeal and Associates, Seattle, WA) used non-uniform rational B-splines (NURBS) to mathematically represent curves, surfaces and solids, applicable to anatomic shapes. The starting point was to design the surface of the femoral component (Fig. 1). Geometrical parameters in both frontal and sagittal planes

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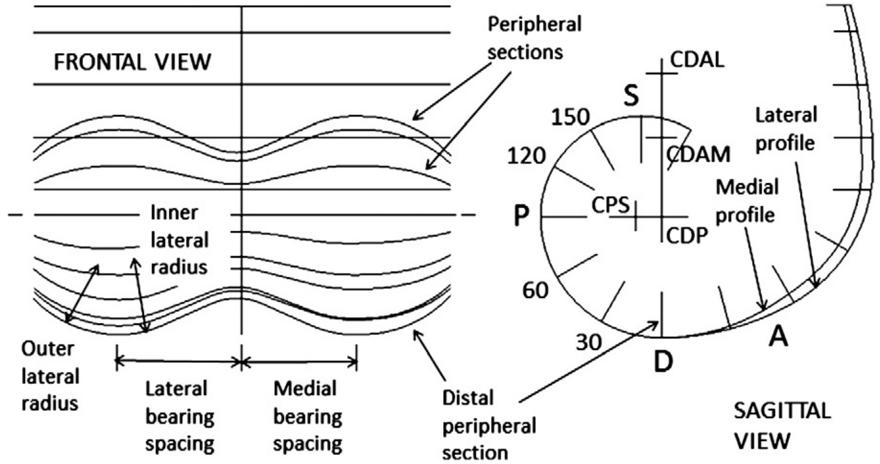

Fig. 1. Frontal and sagittal views of the curves used to construct the femoral surfaces. A = anterior, D = distal, P = posterior, S = superior. CDP = center of arc from D to P, CPS = center of arc from P to S, CDAM = center of arc DA medial, CDAL = center of arc DA lateral. The numerals show the angular rotation, or flexion angle.

were used [26], and the same arcs were used for both the lateral and medial condyles, except for a steeper medial than lateral profile, distal-anteriorly (see location A in Fig. 1), to allow for a more dished tibial surface to limit AP displacements.

Peripheral sections were then specified, defined as a section on a plane perpendicular to the sagittal sections at any point around the sagittal periphery from the superior point of the trochlea to the posterior condyles. The frontal trochlea sections were V-shaped with a rounded base, to be compatible with a retained anatomic patella. The main geometrical parameters for the condylar sections were the medial–lateral bearing spacing and the inner and outer condylar radii, which were constant from 15° extension to maximum flexion. Having specified the peripheral sections and the sagittal profiles, the femoral surface was generated by lofting the former around the latter. This was termed the basic femoral surface (Fig. 2).

2.2. Basic tibial bearing surface

The tibial surface was generated from the femoral surface to reproduce the 'normal mechanics' used as the design criteria, extracted from the references cited above. Overall, the requirement is that the output displacements and rotations in response to a set of input forces and moments are the same for the knee with the TKR implanted as for the intact knee. Specifically, the requirements are:

a) A neutral path of motion (with a femoral–tibial compression force acting down the long axis of tibia) where the displacements and rotations are as defined in Table 1 [24].
b) Small (<3 mm) anterior–posterior (AP) laxity on the medial side.
c) Posterior lateral contact point in high flexion consistent with the displacements and rotations in (a) above.
d) Rotational laxity as defined in Table 1, for specific force/torque conditions. The laxity is relatively small (<3°) at the extremes of extension and flexion.
e) AP laxity on the lateral side to accommodate the rotational laxity.

Qualitatively, the above can be described as 'medial stability–lateral mobility–lateral rollback in high flexion'. Flexion of the femur was defined to be about axis ZF (Fig. 2). The axial rotation was applied about an axis through the medial side 23 mm from the center (point AR in Fig. 2) which is consistent with the medial pivot behavior determined in previous studies [13,16–18,24,25]. It is noted that the maximum external rotation, occurring at 135° flexion, was reduced compared with the anatomic knee, to avoid the lateral femoral condyle from reaching the posterior edge of the tibial component. Posterior femoral displacement, applied at higher flexion angles, was applied along the negative XT-axis [27,28]. The rotational and AP laxities about this neutral path allow for different motion paths depending on loading conditions and muscle activity [29,30]. The external rotational laxity values were higher than the internal [14,24].

The femoral surface was then placed in the multiple positions based on the data of Table 1, to form a composite (Fig. 3). The distal surface of the composite defined a tibial surface that would accommodate the multiple femoral positions. The composite was inverted and a drape function was used for smoothing to produce the basic tibial surface (Fig. 3). The features were a shallow lateral surface in the anterior–posterior direction; a relatively dished medial surface; steeper sagittal sections at the anterior and posterior of the medial side; and a saddle-shaped intercondylar region.

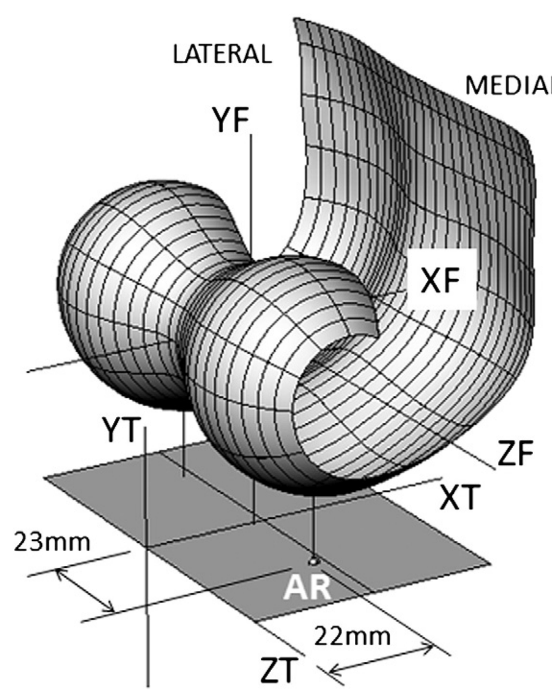

Fig. 2. The basic femoral surface generated by lofting the peripheral sections. The tibial surface is represented by a horizontal plane with dimensions 48 mm × 76 mm. The femoral and tibial axis systems are shown. For internal–external rotation, the femoral component is rotated about point AR on the medial side of the tibia.