Optimizing Acetabular Component Position to Minimize Impingement and Reduce Contact Stress

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Component impingement due to poor positioning can limit range of motion after total hip arthroplasty. Contact stresses on ultra-high molecular weight polyethylene are also dependent on the orientation of the acetabular component. In this study, a computer kinematic model was used to determine the effects of component position and variation of head:neck ratios on prosthetic impingement and hip range of motion, and a finite element model was employed to calculate polyethylene stresses at different cup positions.

Materials and Methods
Kinematic Analysis
A three-dimensional total hip prosthesis with a hemispherical acetabular cup, femoral neck diameters ranging from 10 to 12 mm, and head sizes ranging from 22 to 32 mm was generated (Fig. 1). The maximum range of motion of the hip was measured, before impingement of the neck on the cup liner, for acetabular component abduction angles ranging from 35° to 55° and for acetabular component anteversion angles ranging from

Fig. 1
Computer model used for kinematic analysis. The head diameters ranged from 22 to 32 mm, the neck diameters ranged from 10 to 12 mm, and the liner outer diameter was 50 mm.

Fig. 2
Liner with a wide chamfer that was offset 2 mm above the center of the head to increase range of motion.

Fig. 3
Finite element model of the liner, generated in MARC, with 5184 hexahedral elements. The liner inner diameter was 28 mm, and the outer diameter was 50 mm. The components of the resultant load applied through the head are shown. The head was modeled as a rigid body (not shown).
The maximum range of motion can be described as a cone with its apex at the head center. The base of the cone depicts the range of motion before impingement for each head:neck ratio. Increasing the head:neck ratio increased the range of motion (see Table I for numerical data).

Cones are used to depict the range of motion before impingement for different chamfer offsets. Chamfer offsets above the center of the head increased the range of motion, while offsets below the center of the head reduced the range of motion.

Lateral view of the right hip. The maximum hip range of motion is depicted for each acetabular orientation (35°, 45°, and 55° of abduction and 0°, 10°, 20°, and 30° of anteversion).
0° to 30°. The effect, on the range of motion of the hip, of a wide chamfer that was offset 1, 2, or 3 mm above or below the center of the head was also analyzed (Fig. 2).

Finite Element Analysis
A model of a total hip prosthesis was generated with a finite element analysis program (MARC; MSC Corporation). The acetabular liner was modeled as a hemisphere with an inner diameter of 28 mm and an outer diameter of 50 mm. The liner was composed of approximately 5000 eight-node hexahedral elements (Fig. 3). The femoral head was modeled as a spherical rigid body (28 mm in diameter), while the metal backing of the liner was modeled as a hemispherical rigid body (50 mm in diameter). The viscoelastic material properties of the elements of the liner were modeled with use of stress-strain and stress-relaxation data obtained from experimental testing of ultra-high molecular weight polyethylene cylinders. A load representative of that generated during the stance phase of level gait was applied through the femoral head. The magnitude and direction of the resultant force were taken from previously published in vivo hip telemetry measurements (three times body weight in a 63-kg [139-lb] individual, resulting in a hip force of 1682 N in the superior direction, 727 N in the medial direction, and 765 N in the posterior direction). Keeping the direction and magnitude of the applied load constant, contact stress and area were calculated for acetabular component abduction angles ranging from 35° to 55° and acetabular component anteversion angles ranging from 0° to 30°. The effect, on contact stresses, of a wide chamfer that was offset 1, 2, or 3 mm above or below the center of the head was also calculated.

Results
Range-of-Motion Analysis
Head:neck ratios substantially affected hip range of motion
The maximum range of motion before impingement was plotted as a cone. The base of the cone denoted the overall range of motion available. Larger head:neck ratios increased the base of the cone (Fig. 4). The addition of a wide chamfer to the hemispheric liner also affected the range of motion. Offsetting the inner edge of the chamfer above the head center increased the range of motion, while offsetting it below the head center decreased the range of motion (Fig. 5).

Acetabular orientation defined the orientation of the cone in space and substantially affected the individual components of hip range of motion. Acetabular abduction angles of <45° reduced flexion and abduction, while higher angles tended to reduce adduction and rotation (Fig. 6). Acetabular anteversion increased flexion and internal rotation but re-
duced extension and external rotation. Overall, acetabular abduction angles between 45° and 55° permitted better range of motion and stability when combined with appropriate acetabular and femoral anteversion.

**Polyethylene Stress Analysis**

A consistent decrease in contact area with an increase in the acetabular abduction angle (from 35° to 55°) and with a corresponding increase in mean and peak contact stresses was predicted with use of the finite element model (Fig. 7). At each acetabular abduction angle, increasing cup anteversion from 0° to 30° resulted in an increase in contact area and a decrease in von Mises stresses, contact stresses, and shear stresses. The stresses at the posterosuperior edge of the liner also increased with increasing abduction: there was a 55% and 69% increase in von Mises stresses from 35° to 45° and from 35° to 55°, respectively. When the body weight was increased from 63 kg (139 lb) to 90 kg (198 lb), peak contact stresses increased by 36%.

A wide chamfer that was offset above the center of the head also decreased contact area and increased stresses in the liner. The inner bearing surface area of the liner decreased in a linear fashion from 2032 mm² to 1144, 1056, and 968 mm² for the 1, 2, and 3-mm offsets, respectively. A corresponding increase in contact stresses was noted for the three chamfer offsets tested (Figs. 8-A through 8-D).

**Discussion**

Larger head:neck ratios increased hip range of motion. However, this model did not account for bone and soft-tissue impingement. Data have been reported that suggest that, at larger head:neck ratios (especially with 32-mm-diameter heads), range of motion may be restricted by osseous rather than prosthetic impingement. The addition of a wide chamfer to the liner design resulted in an increase in overall range of motion if the inner edge of the chamfer was offset above the center of the head. The range-of-motion cone angle increased in a linear fashion with the magnitude of the chamfer offset.

There is a complex interplay between femoral and acetabular orientation angles. Acetabular abduction is often constrained by available bone coverage, while femoral anteversion may be dictated by femoral shaft geometry. For each combination of acetabular abduction and femoral anteversion, there is an optimum range of acetabular anteversion that creates the potential for maximum range of motion without prosthetic impingement after total hip arthroplasty. Cup abduction angles between 45° and 55°, when combined with appropriate acetabular and femoral anteversion, resulted in the maximum overall range of motion and stability with respect to prosthetic impingement.

The finite element analysis suggests that peak contact stresses range between 4.5 and 5.5 MPa for a hemispheric liner (without a chamfer), depending on the abduction angle and the anteversion angle. These stresses are well within the yield strengths reported for ultra-high molecular weight polyethylene. However, these stresses were generated with use of a very benign hip load representative of the stance phase of level walking by a 63-kg (139-lb) individual. Increasing the body weight to 90 kg (198 lb) substantially increased contact stresses. Much higher hip loads are generated during stair-climbing, rising from a chair, and more vigorous activities. Therefore, care should be taken when approaching the higher limit of cup abduction. Cup abduction reduces contact area and thus increases contact stresses. In addition, higher stresses are generated near the posterosuperior edge of the liner. These results suggest that these stresses can be alleviated by judicious anteversion of the liner. Overall, the results suggest that cup abduction angles at or slightly higher than 45° provide the optimal combination of adequate range of motion and low contact stresses. If higher abduction angles are necessary, appropriate anteversion helps to reduce contact stresses.

Chamfers are usually designed to increase range of motion. However, chamfer offsets above the head center also increase contact stresses and should be used in moderation. Other design features that can affect range of motion and contact stresses but were not evaluated in the current study include elevated-rim, high-wall, anteverted, and lateralized liners.

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**References**
