Kinematic and Wear Performance of a Novel Cruciate Retaining Biomimetic Implant Manufactured from Advanced Vitamin-E Stabilized Material

Kartik Mangudi Varadarajan, PhD, Thomas Zumbrunn, MS, Harry E. Rubash, MD, Henrik Malchau, MD, Guoan Li, Ph.D., Orhun Muratoglu, PhD.
Massachusetts General Hospital, Boston, MA, USA.

Disclosures: K. Mangudi Varadarajan: 1; MAKO Surgical. 3A; Merck (Spouse). 3B; Orthopedic Technology Group, CeramTec GmbH. T. Zumbrunn: None. H.E. Rubash: 1; MAKO Surgical. 3B; MAKO Surgical, Access Mediquip. 4; Orthopedic Technology Group. 7; Lippincott, Williams & Wilkins. H. Malchau: 1; Smith & Nephew, MAKO Surgical. 3B; Smith & Nephew; MAKO Surgical. 3C; Biomet. 4; RSA Biomedical, Orthopedic Technology Group. 5; Smith & Nephew; Depuy; Biomet; Zimmer; MAKO. 6; Smith & Nephew. G. Li: 1; MAKO Surgical. O. Muratoglu: 1; Zimmer, Biomet, Corin, Conformis, MAKO Surgical. 2; Zimmer, Corin. 4; Orthopedic Technology Group. 5; Biomet, Depuy, MAKO Surgical.

Introduction: Normal knees show activity dependent kinematics in vivo. During high flexion activities like deep knee bend (DKB) and chair-sit, normal knees show an overall medial pivot motion with greater lateral than medial condyle rollback [1,2]. During activities like stair climbing normal knees show variable pivot location with nearly equal medial and lateral condyle motion [3]. Contemporary Total Knee Arthroplasty (TKA) implants have been unsuccessful in restoring this activity dependent behavior of the native knee. While bearing materials have evolved steadily, bearing designs have changed minimally. Consequently, a sizeable proportion of TKA patients remain dissatisfied with how their knee feels and functions following surgery. We hypothesized that: (a) advanced biomimetic bearing surfaces engineered directly from in vivo healthy knee kinematics can better restore activity dependent kinematics of normal knees; (b) such biomimetic implants manufactured from advanced polyethylene can provide superior performance than contemporary implants manufactured from conventional materials.

Methods: 3D knee models of 40 normal subjects (24 male, 16 female, age 29.9 ± 9.7 years), were created from magnetic resonance imaging and bi-planar fluoroscopy was used to capture 3D knee motion during deep knee bend. The individual bone models and kinematics were combined to create a 3D virtual representation of an average normal knee and its motion pathway. An advanced biomimetic CR implant was then engineered by moving the femoral component through the average in vivo kinematics to carve a corresponding tibial articular surface. Unlike the symmetric medial/lateral dished geometries of contemporary CR tibias, the biomimetic CR tibia had an anatomic geometry with a moderately dished medial plateau, and a convex lateral plateau similar to native knees. Simulated deep knee bend, chair-sit, stair-ascent, and stair-descent kinematics of the biomimetic CR were compared to that of two contemporary CR implants (NexGen CR, Zimmer Inc; Vanguard CR, Biomet Inc) in LifeModelerTM KneeSIM. Anteroposterior motion of the medial and lateral femoral condyle centers was measured relative to a tibial origin. The collateral ligaments, posterior cruciate ligament, quadriceps, and overall capsular tension were modeled. The soft-tissue insertions were obtained from the average knee model, and the mechanical properties were obtained from literature.
Five million-cycle (MC) knee simulator wear performance of the biomimetic CR was compared to that of a contemporary CR manufactured from conventional material. Biomimetic CR tibial inserts of identical sizes were machined from a 0.1 wt. % blended vitamin-E / GUR1020 stock that had been irradiated to 100 kGy, mechanically annealed to a compression ratio of 2, and thermally annealed. Both implants were EtO sterilized after machining and articulated against identical CoCr femoral components. All samples were subjected to ASTM F2003 accelerated aging prior to testing.

Results: During the simulated activities, the biomimetic CR implant showed activity dependent kinematics similar to the normal knees in vivo. During the simulated DKB and chair-sit activities, the Biomimetic CR showed medial pivot motion with greater lateral than medial condyle rollback (DKB - 7.2 mm medial vs. 13.2 mm lateral; chair-sit - 5 mm medial vs. 11.2 mm lateral). In contrast, both contemporary CR implants showed no medial pivot during DKB or chair-sit. In NexGen CR, the femur also underwent paradoxical anterior sliding from 0° to 60° flexion. In Vanguard CR, the femur showed nearly equal medial and lateral condyle rollback. During stair-ascent, in each implant the medial and lateral condyles moved by similar amounts in the same direction. During this activity, kinematics of the biomimetic CR and Vanguard CR were more similar than that of NexGen CR.

The wear study showed 84% reduction in wear rate for the aged biomimetic tibial components manufactured from the vitamin-E UHMWPE compared to the aged contemporary tibial components manufactured from conventional UHMWPE (13.8 ± 3.3 mg/MC vs. 84.9 ± 13.7 mg/MC). Beginning at the 3MC data point the conventional samples also began to exhibit signs of oxidative delamination that grew worse as the test progressed.

Discussion: The biomimetic CR design, reverse engineered from normal knee motion, was able to mimic activity dependent kinematics of normal knees, unlike contemporary implants. The biomimetic implant reproduced the medial pivot behavior seen in normal knees during deep knee bend and chair-sit, as well as the variable pivot pattern displaced by normal knees during stair climbing [1-3]. Further, the biomimetic implant manufactured from vitamin-E polyethylene showed vastly superior wear performance than a contemporary implant manufactured from conventional polyethylene. Thus, implants with biomimetic bearing surfaces manufactured from advanced materials may provide a more normal feeling knee, while also increasing implant longevity.

Significance: Total knee arthroplasty implants with biomimetic bearing surfaces can better replicate activity dependent kinematics of the normal knees than contemporary implants. Such biomimetic designs manufactured from advanced materials may provide a more normal feeling knee, while also increasing increase implant longevity over contemporary implants manufactured from conventional materials.
Deep Knee Bend Simulation

Chair Sit Simulation

Stair Ascent Simulation

ORS 2015 Annual Meeting
Poster No: 0855