FIBERSCOPE VISUALIZATION OF TOTAL KNEE REPLACEMENT CONTACT KINEMATICS DURING IN VITRO SIMULATION

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ABSTRACT
Optimization of total knee replacement (TKR) design and wear behavior requires the study of bearing contact mechanics. In this study, a novel fiberscopic imaging method was developed and combined with dynamic TKR simulation to visually quantify dynamic TKR contact areas in vitro. Contact areas between transparent TKR tibial inserts and metallic femoral components were captured using opaque lubricant media and a fiberscopic high-speed video camera within the simulator. Walking and stair descent loading patterns were characterized. Centroid location and contact pathways were calculated to determine pathway velocity and cross-shear characteristics. Overall, contact velocities ranging from 0 to 233 mm/sec and crossing angles ranging from near 0 to 90 degrees were found during this study. These results provide a basis for wear testing and cross-shear modeling of TKR materials, leading to more accurate predictions of wear behavior in these implants.

INTRODUCTION
The wear behavior of a TKR can be evaluated in vitro using a wear simulator that mimics the environmental and loading conditions in the knee. Quantifying the contact area and its location during dynamic simulation is difficult however. Currently available thin-film pressure-sensitive techniques interfere with joint articulation, and often have limited application under dynamic conditions. In this study, a novel experimental technique was developed whereby direct imaging of TKR bearing contact was achieved through the use of a transparent tibial insert within a total knee joint wear simulator. In this manner, direct dynamic measurements of tibiofemoral contact area in a TKR while under physiological loading could be made in vitro.

MATERIALS AND METHODS
An Instron/Stanmore force-controlled total knee joint wear simulator (Instron, Inc, Canton, MA) was used to apply static and dynamic loading to a TKR system (2). Custom fiberscopic supports and lubricant containment systems were fabricated within the wear testing simulator tibial cup holder. Lexan bases were installed in the bottom of the cups onto which the test components of interest could be secured. A 50% bovine serum (BS) solution (Hyclone, Logan, UT, USA) was used as a lubricant. Indian ink (Specialist Crafts Ltd., Leicester, UK) was added as a contrast agent at a ratio of 8.5:1 (BS solution to Indian ink). During surface contact the lubricant was displaced, allowing visualization of the bearing contact areas.

For calibration, flat Caroplastic sheets (Carolina Biological Supply Company, Burlington, NC, USA) were used in combination with spherical stainless steel components of known geometry to calibrate the fiberscopic set-up and validate the image analysis contact area results compared to a Hertzian ball-on-flat contact model. A high-speed camera (MotionScope PCI 8000S, Redlake Imaging Corporation, Morgan Hill, CA, USA) with an image resolution of 240 x 480 pixels was coupled with an 11-mm diameter fiberscope (Olympus Industrial America, Inc., Orangeburg, NY, USA) and high intensity light source (AutoBrite Illuminator II, Dyonics, Inc., Andover, MA, USA) was utilized to capture the image data at a rate of 125 frames/second. Image analysis was performed using Image J, (National Institutes of Health) and automated grayscale thresholding procedures to insure reproducible determination of contact areas and centroid locations.

For dynamic TKR testing, a transparent tibial insert made of Caroplastic was impression molded from a clinically successful, semi-conforming, cruciate retaining tibial insert.
(Natural Knee II, Zimmer, Inc., Warsaw, IN, USA). Static axial loading at different femoral flexion angles was conducted, followed by physiologic dynamic loading simulation of previously published walking and stair descent loading patterns (1). Dynamic contact areas were recorded during these simulations, and measures of centroid area location, velocity and pathway statistics were compiled.

RESULTS

Uni-axial tensile tests (ASTM D638, 50mm dog bones, 1mm/min loading rate, n=10) determined the Caroplastic average Young’s Modulus to be 623 ± 178.4 MPa. Friction coefficients determined during static and dynamic friction tests (15.5mm stainless steel spheres, 2.5N load, 50mm/sec, 50% bovine serum lubricant) ranged from 0.417 to 0.621 (dynamic to static).

Clear video images of the femoral-tibial surfaces in contact were possible under both static and dynamic conditions. Calibration trials comparing circular intender contact area and Hertzian theory yielded good correlation when based on apparent circular perimeter (figure 1). Automated grayscale thresholding methods provided reliable perimeter contouring of contact areas, although manual filling of discrete image contact area voids was sometimes necessary to satisfy a continuous contact patch criteria. Images of raw and processed medial/lateral tibiofemoral contact under loading are shown in figure 4.

Figure 4. (Left) Raw (a) and processed (b) images of medial and lateral tibiofemoral contact under static loading at 0° flexion. (Right) Observed medial (red) and lateral (yellow) contact area measurements based on perimeter contouring showing good agreement with Hertzian contact theory (white).

The total contact areas measured over one full walking cycle were 254.99mm² and 268.64mm², while total contact areas measured over one full stair descent cycle were 286.24mm² and 232.35mm² (medial and lateral condyles respectively). Centroid pathway travel distances per cycle were 68.1mm and 56.6mm for the walking cycle and 56.1 and 53.9mm for the stair descent cycle (medial and lateral condyles respectively). Area centroid tracking results indicated that walking pathways produced an average of 10 and 8 contact pathway crossings per cycle, while stair pathways produced only 5 and 3 contact pathway crossings per cycle (medial and lateral condyles, respectively). The stair pathways were characterized as having a higher frequency of reversals (crossings of less than 15 degrees) than the walking pathways. The maximum centroid travel velocities were found to be least in the lateral stair contact pathway (94mm/sec) and greatest in the medial walking contact pathway (233mm/sec). Overall, crossing angles ranging from near 0 to 90 degrees were found for both condyles and loading patterns.

DISCUSSION AND CONCLUSION

This method offers the first opportunity to directly visualize the contact mechanics of at TKR under dynamic conditions. The contact areas and A/P displacement values found with this imaging method correlate well with published values, and are closely related to the wear tracks found in clinical retrievals. This method offers a practical experimental test bed from which investigations of kinematics, lubrication and wear can be undertaken. With greater regulation of light source intensity, this method offers the potential of direct measurement of contact stress based upon the correlation of image intensity and surface contact pressure. Limitations of the current study include the substitution of Caroplastic for UHMWPE and the distortion of the field of view from the use of a fiberscope. Future studies employing this method should focus on utilizing a transparent tibial material with frictional and material properties closer to those of UHMWPE, and a setup that allows visualization of the entire tibial insert surface during testing rather than imaging one condyle at a time.

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