DESIGN AND CONSTRUCTION OF A TEST RIG FOR INVESTIGATING CONTACT PRESSURES WITHIN THE KNEE JOINT COMPARTMENT: TO WHAT EXTENT DO BIOMECHANICAL MISALIGNMENT AND EXCESSIVE AP SHEAR FORCES CAUSE DEGENERATIVE CHANGES OVER TIME?

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ABSTRACT

There are many factors contributing to the development of osteoarthritis of the knee. Joint trauma, obesity, prolonged occupational stress, genetics, age, and muscle injury all play a role in the degenerative process. Additionally, gait analysis studies have found that small differences in the resultant force vector across the knee's center of rotation exist in normal, symptom-free people. We believe that this slight varus or valgus misalignment is a possible biomechanical risk factor for osteoarthritis and that the initial shock of early stance creates abnormal contact pressures in misaligned knees. Over time, these abnormal localized stresses may destroy the mechanical integrity of the affected areas of articular cartilage. To investigate this hypothesis, two different designs for a testing apparatus were considered: a dynamic rig capable of including simulated muscle forces and six degrees of freedom and a less complicated rig with discrete positions and four degrees of freedom. The latter was chosen for its feasibility and suitability and was designed to subject cadaveric knee joints to normal and abnormal variations in loading on an MTS Model 858 Bionix Test System. The testing rig was designed in three dimensions with Catia (V5.6), a 3-D Modeling software system. It consisted of a tibial fixture with unconstrained internal/external rotation and XYZ translation and a femoral fixture incorporating the natural 6 degrees of varus of the knee as well as the following possible flexion angles: 0°, 5°, 10°, and 15°. During future testing, pressure measurements can be made using the K-Scan System (Tekscan Inc., Boston, MA) or the Flexiforce Paper Thin Sensor (Cooper Instruments, Warrenton, VA).

INTRODUCTION

A complete understanding of the biomechanical characteristics of the knee joint in gait studies and similar research is fundamental to understanding how degenerative changes can be prevented or treated before they become too advanced. The assumption made is that osteoarthritis is, at least in part, caused by imperfect biomechanical alignment of the femur with respect to the tibia. This can occur as a result of injury, excess weight, abnormal gait pattern, or from a slight varus or valgus congenital deformity [2]. Genetic predisposition and other effects then aggravate and accelerate the degenerative process, causing pain and further abnormalities in joint kinematics, leading to damage in adjoining compartments. This conclusion is supported by the fact that osteoarthritis of the medial compartment is almost ten times more prevalent than the lateral one, a finding often attributed to the biomechanical effects of greater medial compartment joint loads and the varus moment seen throughout the stance phase of gait [3].

As a result of this relatively recent emphasis on abnormal biomechanical effects, researchers have studied methods for recreating optimal joint alignment in patients with early osteoarthritic changes. Several authors have shown the beneficial impact of unloader knee braces and shoe wedge insoles [1, 5]. Additionally, gait analysis has been used to demonstrate that osteoarthritic patients attempt to minimize pain by reducing their knee extensor (varus) moments and that females have a greater knee extensor moment than males [4]. This finding may explain, in part, the greater prevalence of osteoarthritis in women. A link between varus misalignment and medial OA and valgus misalignment and lateral OA has also been recently established [6].

All of these studies point to the possibility that slight differences in the gait patterns of normal subjects with the resulting misalignment of the knee joint can lead to abnormal local stresses on either the medial (and in some cases, lateral) compartment of the knee. The purpose of this study was to develop a testing device capable of measuring the inter-compartmental contact pressures in a human cadaveric knee specimen as various load configurations (slight varus/valgus, internal/external rotation, and anterior/posterior shear forces) were applied.

RESULTS

The design was successfully completed to meet all necessary testing specifications. Final assembly views of the tibial fixture can be seen in Figures 3 and 4. The central feature of this design is the innovative frictionless thrust ball bearing function. The four thrust bearings seen in Figure 4 allow the knee specimen to freely translate as well as internally and externally rotate once the loads are applied with the 858 Bionix MTS. The square tibial pot design allows for more straightforward bone cement fixation due to its increased surface area. Insertion of the cadaveric tibia can be also be accomplished at optimal alignment by utilizing the extra area.

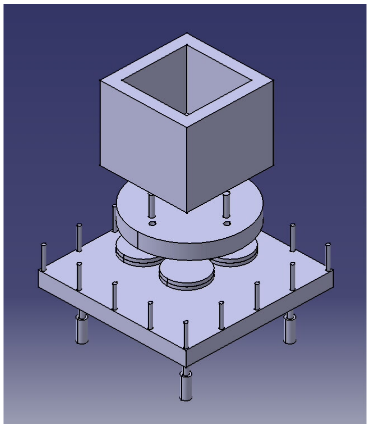

Figure 3: Isometric view of the assembled tibial fixture.

A total of six parts were designed for the tibial fixture. These include: the square tibial pot, the four pegs stabilizing the pot onto the circular steel plate below it, the square plate seen with 16 pegs along its perimeter, and the four half peg/half screw attachment pieces seen at the bottom of the assembly. The pre-manufactured thrust bearings can be seen at the center of Figures 3 and 4, between the square plate and the circular plate. The frictionless ball bearings of these parts are only visible in Figure 4. Material for the square tibial pot is Delrin plastic. All other parts are designed for manufacture in Type 340 Steel. Friction was minimized in the design by ensuring that the top surface of the square steel plate is hardened to a Rockwell hardness of C60-70 in order to match the mechanical properties of the frictionless ball bearings it comes into contact with. The specifications of the square plate also call for high precision in flatness during the machining process for optimal rolling possibility of each bearing. The pegs fitted along the perimeter of the square plate function as safety device, preventing the thrust bearings from escaping the area. The entire mechanism is fixed securely to the platform of the 858 Bionix MTS via the half-screw/half peg attachment pieces.

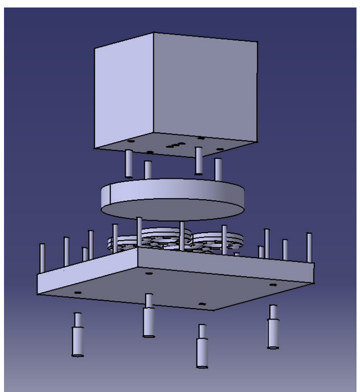

Figure 4: Bottom-Isometric view of the assembled tibial fixture.

The femoral fixture can be seen in Figures 5 and 6 below. This mechanism attaches to the actuator of the MTS 858 Bionix via the plunger adapter piece seen above the conical piece in the figures. There are four distinct conical pieces, each geometry allowing for a desired flexion angle of 0°, 5°, 10°, or 15°. The conical shape also ensures that the applied load from the MTS machine is evenly distributed. The next piece's main purpose is to account for the natural 6° of varus seen in all normal knees. This adapter part has two slotted pockets where bolts can be inserted in order to fix the assembly to the femoral pot. The conical part was *not* fastened to this adapter in any way. The purpose of this was to permit deliberate varus or valgus misalignment during testing by moving the conical part medially or laterally. Lastly, the femoral pot was nearly identical to the tibial pot previously described. It was responsible for securing the cadaveric femur (with bone cement) into the testing apparatus. Both the femoral pot and the tibial pot incorporated three center holes so that the bone cement and knee specimens could be removed after testing via standard freezing and hammering techniques.

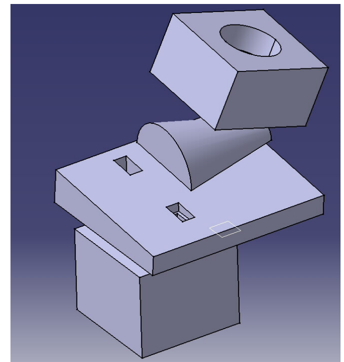

Figure 5: A top - isometric view of the assembled femoral fixture.

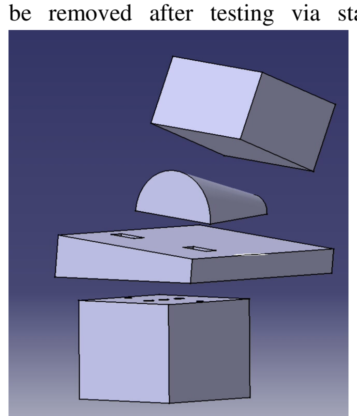

Figure 6: An additional view of the assembled femoral fixture.

DISCUSSION

Future elements of this research include the manufacturing of the test rig and preliminary testing on a representative artificial knee model. Calibration and integration of MTS software to meet design goals must also be performed. If this is successful, testing of cadaveric specimens can take place and the data can be analyzed and evaluated. The device may require reconfiguration of particular components or the addition of more dynamic features in order to yield the required results. If the hypothesis proves true, the correlation between abnormally high forces in articular compartments and the location of subsequent OA development may be investigated further.

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