Proceedings of IMECE2004:
2004 ASME International Mechanical Engineering Congress and R&D Expo
November 13-19, 2004 Anaheim, California

IMECE2004-61226

DEVELOPMENT OF PRE-CLINICAL PATELLAR COMPONENT TEST FOR TOTAL KNEE ARTHROPLASTY

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ABSTRACT

Patellar component failure accounts for the majority of complications with total knee arthroplasty procedures [1]. Current patellar component tests involve loads that do not categorize failures as seen in clinical data. The aim of this project is to define the forces that lead to failure and design a test that can predict these failures.

Clinical data reveals that the primary mode of failure of patellar components involves polyethylene wear most prominent at the lateral aspect of the component in various types of patella designs. Research on normal knee anatomy, kinematics and forces indicates that quadriceps tension results in a net lateral force exerted on the patella. This force, combined with the lateral to medial motion of the patella and its contact with the femoral condyles during 60° to 140° flexion, is theorized to be the contributing factor that leads to the observed clinical failure.

INTRODUCTION

In a recent study, Sharkey and his colleagues [2] determined that polyethylene wear accounts for approximately 25% of total knee revisions and 6% of revisions are due to patellofemoral complications.

The goal of this project is to design a preclinical test that can predict the initiation of patellar component deformation that leads to eventual clinical failures. The overlap in the factors that lead to component failure and normal knee forces was used as the basis for the test design and the motivating failure theory is the core of the project.

The project involves two phases: 1) Test development and pilot testing 2) Validation and determination of performance criterion. The failure theory will be tested using a test apparatus that will simulate the loading and motion of the patella during flexion in two planes. After initial evaluations of the test are completed, future analysis will involve development of the proper load criteria that predict clinical failures.

Kinematics

A brief review of knee anatomy and patella features serves as a foundation for understanding the forces involved in patellar movement. The quadriceps muscle is the primary muscle group connected to the patella and is resisted by the patellar tendon which originates from the tibial tubercle.

Hungerford and Barry [3] studied patella tracking during flexion and extension. At full extension the patella is initially on the anterior lateral portion of the femur and medially approaches the trochlear groove during early flexion angles. Next, the patella moves laterally until the component finally rests within the condylar notch. The net result is a C-shaped curve, opening laterally on the knee. The area of contact of the patella changes from the distal end of the patella moving proximally. From 90° to 135° of flexion, the area of contact changes from the central portion of the patella to the lateral and medial facets of the articulating surface. Several studies have confirmed this tracking pattern [4,5,6].

From these studies it is evident that during knee flexion, the patella tracks in a lateral-medial-lateral arc; the patellar-femoral contact area transitions from distal to superior and from the central region to the lateral and medial facets; and, finally during deep knee flexion to the lateral facet.

Biomechanics

The quadriceps muscle exerts the majority of the tensile forces experienced by the patella. Senavongse and his co-workers [7] determined the direction of muscle loading according to the directions of the muscle groups. These forces were proportional to the cross-sectional area of the individual muscle groups. Using this method, 42% of the forces are directed laterally and 23% medially. It is also important to note that during the final thirty degrees of extension, the tibia rotates externally causing a change in the alignment of the quadriceps force and the patellar tendon [3] resulting in a greater lateral force.

For the purposes of this study, it was relevant to determine an approximate model of the anatomical forces during flexion, and consequently a model for the patellofemoral joint reaction force for appropriate load cases. Several studies [8 - 10] have established a pattern of sinusoidal loading for various activities including walking, stair ascent and descent, and squatting and rising. A worst case scenario is described when squatting is considered: maximum patellofemoral forces have been calculated to be 5600 N at 120° of flexion [11] while quadriceps forces have been measured at 1275 N at 110° of flexion [12].

From this research it is evident that during knee flexion, the patellar load increases with a lateral bias. It is also evident that the resistive force of the patellofemoral joint reaction force does not equal the magnitude of the quadriceps force.

Component History and Failure Modes

With a general review of normal patella movement and biomechanics as a foundation, the next step in developing a failure theory was to evaluate the patellar component itself. Stulberg and co-workers [13] documented the failures of metal-backed patellar components; specifically noting complete polyethylene dissociation from the metal backing. Interestingly, Stulberg noted similar patterns of failure between the metal-backed and all-polyethylene components noting that both groups deform in a similar manner and often in the same location: the lateral aspect of the component.

Baech and Kofoed [14] also documented metal backed component failure and asymmetrical wear patterns. Andersen and co-workers [15] echo the results of other metal backed component studies, including the presence of lateral edge wear. Shen [16] reviewed patellar component retrievals and noted asymmetrical wear patterns and polyethylene deformation prominent on the lateral aspect of the patellar component.

Studies concur on the range of motion of patients requiring total knee revision citing that the patient population is becoming younger, more active, and more likely to extend the range of motion, a phenomenon previously unseen in the geriatric population that dominated the total knee arthroplasty population. The range of motion of failed components varied from 80° - 121.5° of knee flexion.

This investigation of component failure reveals a trend towards failure initiation on the lateral aspect of the patellar component. Although this result is independent of component design, the time to failure of metal-backed component was significantly lower than polyethylene components. The range of motion in patients with failed components includes knee flexion above 90°.

METHODS

Design Rationale

The persistence of patellofemoral complications in total knee arthroplasty provides motivation for a review of the patellar component design. Normal knee kinematics and biomechanics impart significant forces on the lateral aspect of the patella and are theorized to contribute to the initiation of patellar component failure in the form of lateral polyethylene wear or delamination.

Further support for this failure theory can be found in the review of patellar tracking in three different total knee designs performed by Chew and co-workers [1]. Each design experienced a lateral shift with increasing knee flexion. Fujikawa [17] also provides insight into the significant change in area of contact, from centrally located along the patellar surface to lateral and medial, with the absence of femoral cartilage. The absence of cartilage accurately describes the conditions of a total knee replacement.

It is therefore important to isolate the following factors: 1) lateral-medial-lateral tracking of the patella; 2) knee flexion angles greater than 90°; 3) patellofemoral contact area at the medial and lateral aspects of the patellar component; 4) physiological load range.

The aim of the test design is to mimic normal knee kinematics and test patellar components used in total knee arthroplasty under normal knee conditions. The goal is to predict the initiation of patellar component failure in the form of lateral deformation or wear in components previously documented to experience this failure mode.

Test Design

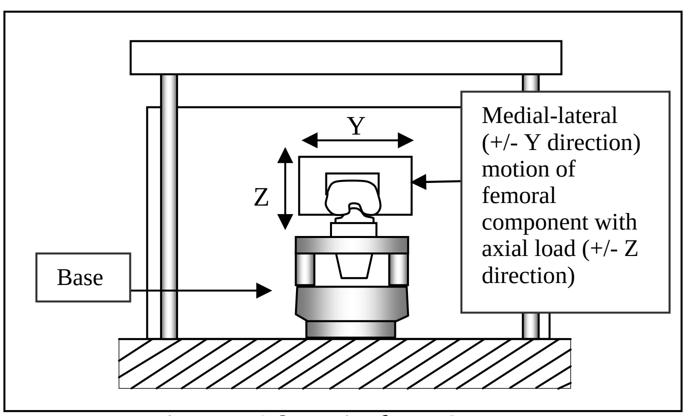

Figure 1. Schematic of Test Apparatus

The patellar component is mounted in a PVC flanged bushing machined to accommodate the patellar component. Care is taken to ensure that the component remained level during fixturing. Next, the bushing is cemented into the tibial tray component of an AMTI Force 5 test machine (Fig. 1). The patella is oriented according to surgical technique for typical total knee arthroplasty. The cylinder is mounted such that it rises above the tibial tray surface to allow adequate clearance of the femoral component during testing. The tibial cup was filled with bone cement so that the cylindrical base is rigidly fixed.

Due to the complexity of the forces involved during knee movement, the test will focus on the failure regions and corresponding ranges of motion. The C-shaped movement of the patella is mimicked in the test by displacing the femoral component in a sinusoidal medial-lateral motion corresponding to the degrees of knee flexion and extension as has been documented in kinematics research [18]. A corresponding sinusoidal force is exerted on the patellar component by the femoral head, which is synchronized with the medial-lateral displacement of the patella (Fig. 2).

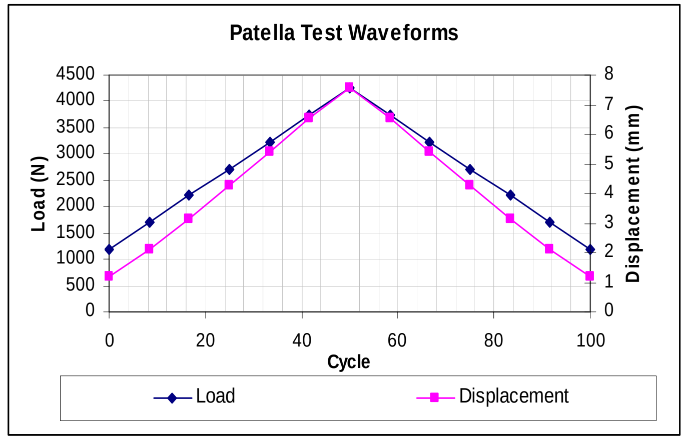

Figure 2. Load and Displacement Waveforms

The femoral head is positioned to expose its radius of curvature, which corresponds to the degrees of flexion from 60° to 120°. The radius of curvature of the component is relatively constant at these flexion angles, therefore the component is held fixed at the 100° position. With this test arrangement, the patellar component will be tested under an adverse worst-case loading scenario that will simulate the physiological kinematics of deep knee bending.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions and support of Zimmer Orthopedics, Dave Blakemore, Les Gilbertson, Frank Jones, Lynn Kirkpatrick, Dr. Bryan Heiderscheit, Dr. Richard Illgen, and the members of the Musculoskeletal Research Lab–University of Wisconsin, Madison.

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