Comparison of Stresses in Four Modular Total Knee Arthroplasty Prosthesis Designs

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ABSTRACT

The current study, compares the mechanical performance of four modular TKA prostheses based on von Mises stress distribution in the tibial insert. Three-dimensional finite element (FE) models of a cruciate retaining type modular prosthesis and three posterior stabilized (PS) type modular prostheses namely: anterior slide, modular post and double cam, were developed. A compressive load of 2600 N was applied to the FE models at flexion angles of 0°, 15°, 30°, 60° and 90°. Von Mises stress was evaluated on all the modular parts of the prostheses and compared with the yield strength of the corresponding material. Von Mises stress in all the parts were below the yield strength of their corresponding material except for tibial insert of anterior slide design at high flexion angle. Von Mises stress above the yield strength in the tibial insert of anterior slide design, was due to edge loading in the post and it demonstrates the likelihood of mechanical failure by delamination type of wear.

KEYWORDS

Cruciate Retaining, Cruciate Sacrificing, Loosening, Posterior Stabilized, Tibial Post, Total Knee Arthroplasty, UHMWPE, Von Mises Stress

INTRODUCTION

The major reasons for the failure and revision of Total knee arthroplasty (TKA) are: polyethylene wear, aseptic loosening, instability and infection. Labek et al. (2011) did a systematic review of national registers and showed that, 1.26 total knee revisions were done per 100 observed component years. Sadoghi et al. (2013) reviewed the worldwide Arthroplasty registers and reported that reasons for TKA revision as: aseptic loosening (29.8%), septic loosening (14.8%), pain (9.5%), wear (8.2%) and others. Fehring et al. (2001) on a study about reasons for early revision (<5 years) on 279 patients found the reasons were: infection (38%), instability (27%), patellofemoral problems (8%) and wear (7%). Narkbunnam and Chareancholvanich (2012) studied the causes for revision in 189 patients and found that the reasons to be aseptic loosening (52%), polyethylene wear (43%) and infection (31%).

Aseptic loosening of the prosthesis is said to be caused by both biological and mechanical responses. Aseptic loosening occurs due to osteolysis, micro-motion of: bone – cement – prosthesis interface and stress shielding (Grewal et al., 1992; Ingham & Fisher, 2000; Lonner et al., 2001). Of which, osteolysis is a direct biological consequence of wear debris from UHMWPE, causing adverse cellular reactions and inflammation (Purdue et al., 2006; Burton et al., 2012). Stress shielding occurs after TKA process, because of high relative stiffness between prosthesis and bone thereby causing major load transfer through the prosthesis. Thus, this leads to weakening and resorption of bone, resulting in loss of bone – prosthesis support, further leading to component loosening (Lonner et
al., 2001). Wear in the tibial insert made of UHMWPE is another major reason for revision surgery and it is a multifactorial issue comprising of the patient, prosthesis and surgical factors. Wear in the tibial insert is influenced by: activity level of the patient, manufacturing of tibial insert, design, alignment and ligament balance during surgery (Mccloughlin & Kavanagh, 2000; McEwen et al., 2005; Naudie et al., 2007).

Under real-time loading, cyclic stresses above the yield strength in the tibiofemoral interface causes: pitting, delamination, change in the microstructure and degradation of UHMWPE (Landy & Walker, 1988; Edidin et al., 1999). When the von Mises stress exceeds the yield strength of the material, plastic deformation occurs. This plastic strain gets accumulated causing a fatigue crack formation and an eventual failure of polyethylene surface layer by delamination (fatigue wear) (Cooper et al., 1993; Kennedy et al., 2000). Von Mises stress which is a measure of delamination type of wear (Kennedy et al., 2000; Cho et al., 2004) can be easily found by FE analysis, unlike experimental testing. Failure can occur in components other than tibial insert due to lack of bone support, thus causing high stresses above the yield strength. For instance, Huang et al., (1999) reported fracture of the femoral component in a patient due to loss of osseous support. Tibial tray failure was also reported in the literature and they were mainly related to design, mal-alignment and inadequate bone support (Boran et al., 2005; Chatterji et al., 2005).

TKA Prosthesis designs have evolved over decades to approach near natural knee function and kinematics. In the natural knee, Posterior Cruciate Ligament (PCL) stabilizes the anterior – posterior (AP) motion. Balancing the PCL is an essential and challenging task during surgery. Generally, PCL damage is noticed during or after the surgery (Wasielewski, 2002). For these reasons, it is logical to sacrifice the PCL. Based on whether PCL is retained or sacrificed, the TKA prosthesis is classified into cruciate retaining and cruciate sacrificing or Posterior stabilized (PS) type. PS prosthesis replaces PCL with a cam – post mechanism to limit posterior motion and produce femoral rollback. Even though long-term survivorship results of PS prosthesis are promising (Kelly and Clarke, 2002), post failure in the tibial insert is a key issue influencing long-term survivorship (Mikulak et al., 2001; Bal et al., 2008).

FE method has been generally used in literature to predict the biomechanical behavior of TKA prosthesis under different loading conditions. Static FE models in the literature used component orientation from experimental data, or displacement boundary conditions along with loads, to predict component level stresses (Bartel et al., 1982; Villa et al., 2004; Mündermann et al., 2008). Sathasivam and Walker (1998) used rigid body analysis along with FE analysis, to predict fatigue failure in the tibial insert. Bartel et al. (1982) using static FE analysis showed that higher thickness and more conformity in medial – lateral (ML) direction reduces contact stresses in the tibial insert. Huang et al. (2006) studied the effect of post-cam design features and component alignment on stress distribution in the tibial post, under hyperextension. Their study showed that the ‘curve on curve type’ of contact interface can reduce edge loading over the ‘flat on flat type’ contact interface, under rotational mal-alignment conditions. In recent years dynamic FE models has been used to predict kinematics of the prosthesis, along with internal stresses in the components (Godest et al., 2002, Taylor and Barrett, 2003; Halloran et al., 2005).

Anthropometric study on Indian arthritic knees by Shah et al. (2014) shows that knees of the Indian population have smaller femoral and tibial aspect ratio compared western population (Caucasian and American). In another study Shah et al. (2013) virtually implanted western made TKA prosthesis in the femur of Indian arthritic patient to check anatomical conformity. The results showed an overhang of the femoral component in both medial and lateral regions of the femur, which can be detrimental to its long-term clinical performance. With the above two studies as the basis, novel cruciate retaining and PS type TKA prostheses, were designed considering the anthropometric data of Indian arthritic patients. The new designs targeted anatomical, surgical and functional problems related to TKA, specifically observed in the Indian population.

In the current primary and revision TKA surgeries modular components were used in the form of bone augments, stems and cones (Rand, 1998; Panni et al., 2012). But modularity is incorporated in
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