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The influence of surgical malalignment on the contact pressures of fixed and mobile bearing knee prostheses—a biomechanical study

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Abstract

Objective. To investigate the effect of surgical malalignment on contact pressures of fixed and mobile bearing knee prostheses.

Design. An experimental set-up was used to measure contact pressure on the tibial component of fixed and mobile bearing knee prostheses subjected to a compression load and surgical malalignment situations were simulated.

Background. Mobile bearing knee prostheses were designed to decrease tibiofemoral contact pressure by providing both high congruity and mobility. It was also assumed to accommodate surgical malalignment. However, few studies have reported the effect of malalignment of the tibiofemoral joint on contact pressure of fixed and mobile bearing knee prostheses.

Methods. Surgical malalignment situations were simulated to evaluate contact characteristics of tibial component of fixed and mobile bearing knee prostheses. The simulated malalignment conditions include the medial–lateral translation (0.5 and 1 mm), anterior–posterior translation (2 and 4 mm) and internal–external rotation (1°, 3°, 5° and 10°) of the femoral component relative to the tibial component. Fuji pressure sensitive film was used to measure the contact pressure.

Results. The greatest increase of maximum contact pressure in the anterior–posterior maltranslation was 7.63% and 7.62% relative to the neutral contact situation in the fixed and mobile bearing designs respectively. In the medial–lateral maltranslation, there was 23.3% in the fixed bearing design and was 22.0% in the mobile bearing design. In the internal/external malrotation, the greatest increase of maximum contact pressure in the fixed bearing design was 27.1%, which was much higher than the mobile bearing design (22.4%).

Conclusions. The mobile bearing design can reduce maximum contact pressure more significantly than the fixed bearing design when malalignment conditions of the tibiofemoral joint occurs, especially in the internal/external malrotation. The mobile bearing design offers the advantage of self-adjusting over the fixed bearing design to accommodate surgical malalignment.

Relevance

This study revealed that the mobile bearing design has smaller maximum contact pressures than the fixed bearing design in knee prosthesis under malalignment biomechanical tests. This result indicates that there is an advantage for a mobile bearing design over a fixed bearing design to accommodate malalignment conditions caused by surgical technique or soft tissues imbalance in total knee arthroplasty.

Keywords: Mobile bearing; Fixed bearing; Malalignment; Contact pressure; Knee prosthesis

1. Introduction

Polyethylene wear of articular surface is a well-recognized complication of total knee arthroplasty. Factors related to failure of bearing surface of knee prosthesis include material properties of polyethylene, sterilization method, soft tissues balance, the patient's daily activity and the contact pressures on the articular surfaces (Bartel et al., 1986; Collier et al., 1991; McNamara et al., 1994). An asymmetrical wear of the polyethylene component was the common pattern in many retrieval

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analyses (Wasielewski et al., 1994). Therefore, implant alignment and soft tissues balance and the wear of tibial polyethylene component has produced a lot of publications related to these areas (Liau et al., 1999; Liau et al., 2002).

The tibial component in total knee prostheses can be either a fixed or a mobile bearing. The long-term result between fixed bearings and mobile bearings is still a controversial issue (Lewis et al., 1982; Bert et al., 1998; Sanchez-Sotelo et al., 1999). From the biomechanical point of view, mobile bearing design can reduce polyethylene wear and minimize loosening by providing both congruity and mobility in the tibiofemoral joint (Goodfellow et al., 1986). In addition, another advantage of mobile bearing design is to accommodate any surgical malalignment of tibial baseplate and to allow intraoperative adjustment of joint space (Buechel and Pappas, 1989; Buechel and Pappas, 1987).

Many biomechanical studies have demonstrated that contact pressure on the tibial polyethylene component is closely related to polyethylene wear (Rose et al., 1980; Wright and Bartel, 1986). However, most studies in biomechanical tests, finite element analyses and analytical approaches assumed the femoral and tibial components were under an ideal contact alignment. The malalignment of knee prostheses was thought to accelerate polyethylene wear (Rose et al., 1980). Only a few researchers focused on the contact pressures on the tibial polyethylene components under malaligned conditions. Liau et al. (1999) used Fuji pressure sensitive film to study the influence of contact alignment of the tibiofemoral joint of knee prostheses in in vitro biomechanical test. They also used finite element analysis to investigate the effects of malalignment on the stresses in three different conformity designs of the tibiofemoral joint (Liau et al., 2002). Matsuda et al. (1999) utilized the digital electronic pressure sensor to investigate the effect of varus tilt on contact pressures in total knee prostheses. These studies focused on fixed bearing design with different articular curvatures. Matsuda et al. (1998) also measured the contact pressures on the upper- and under-surface of the tibial polyethylene components with a neutral and malrotated tibial tray of three mobile bearing designs and one fixed bearing design. They demonstrated that mobile bearing designs appear to offer advantages over the fixed bearing design when moderate rotational malalignment of the tibial component occurs. However, only the effect of rotational malalignment was considered in their study. To investigate the advantages of mobile bearing designs for accommodating surgical malalignments in the medial–lateral (ML) and anterior–posterior (AP) translations and internal–external (IE) rotation more clearly, this study was undertaken to compare the contact pressures on the tibial component in fixed bearing and mobile bearing knee prostheses under malaligned conditions.

2. Methods

A commercial knee system (U-knee system, United Orthopedic Co., Taipei, Taiwan) with a flat-on-flat design in the coronal plane and a semi-conformity design in the sagittal plane and 5 degrees of posterior slope in the tibial insert was used. The current design in the tibial component of U-knee system is a fixed bearing. The locking mechanism of the tibial component was modified to become a mobile bearing system. The mobile bearing knee prosthesis allows 1 mm translation in both ML and AP directions and 15° IE rotation of the tibial insert relative to the tibial baseplate. The curvatures of tibiofemoral joint in the mobile bearing design was identical with the fixed bearing design.

The material testing system (Bionix 858 II, MTS system Co., Eden Prairie, USA) was used to apply a compression force to the implant. The medium grade Fuji film with a sensitivity range of 9.8–49 MPa (Fuji Photo Film, Tokyo, Japan) was used to measure contact pressure. For calibration of the Fuji pressure sensitive film, an aluminum bar and polyethylene block with a

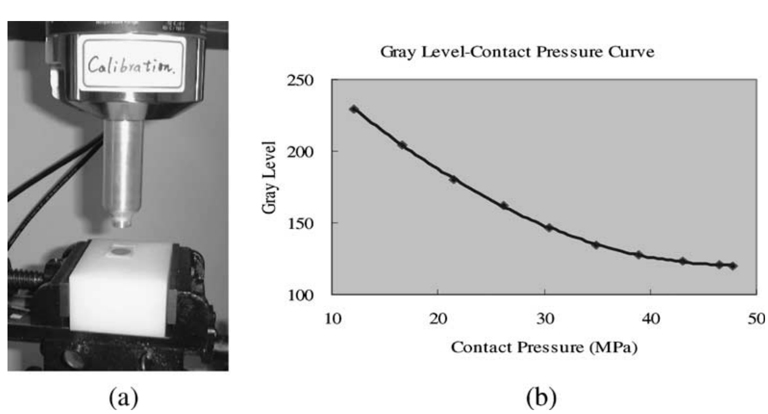

Fig. 1. Fuji prescale sensitive film calibration scheme: (a) Fuji film calibration set-up; (b) gray level–contact pressure curve.

Fig. 2. The experimental set-up.

calibration scheme (Fig. 1) was used to estimate the contact pressure and compare with previous calibration studies (Wang et al., 1995).

A compression force of 3000 N with a loading rate of 200 N/s (Liau et al., 1999), was applied to the implant at zero degrees of knee flexion. The femoral and tibial components were held in a custom made fixture that mounted in the testing system (Fig. 2). The tibial fixture can be adjusted for the AP and ML translation. After aligning the normal contact alignment (Cheng et al., 1998), the surgical malalignment was simulated. The simulated malalignments included AP maltranslations (2 and 4 mm), ML maltranslations (0.5 and 1 mm) and IE rotations (1°, 3°, 5° and 10°) of the femoral component relative to the tibial component (Liau et al., 1999). Each condition was tested using a new polyethylene insert and was repeated three times to ensure reproducibility. The comparison of contact pressure on the tibiofemoral joint of fixed bearing and mobile bearing knee prostheses was performed to investigate the accommodation of mobile bearing knee on surgical malalignment. A student t-test was used for statistical analysis and the level of significance was set at $P = 0.05$.

3. Results

The typical results of the contact pressure distribution of the neutral and malalignment positions measured by Fuji prescale sensitive film were shown in Fig. 3. The maximum contact pressure (MCP) of fixed bearing design was 23.6 MPa, which was significantly higher than the mobile bearing design (22.3 MPa) ($P < 0.05$) under the normal contact alignment. The MCP of fixed bearing design was also significantly higher than the mobile bearing design when the femoral component was translated posteriorly 2 and 4 mm (Fig. 4), and was translated medially or laterally (Fig. 5). The greatest increase of MCP in AP maltranslation was 7.63% and 7.62% relative to the neutral contact alignment in the fixed and mobile bearing designs respectively. In ML

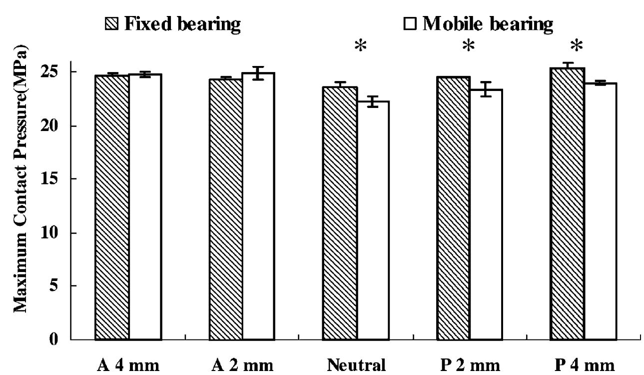

Fig. 4. MCPs in the anterior (A) and posterior (P) maltranslation (mm) of femoral component relative to the normal contact alignment at 0° flexion; (*) statistically different between fixed bearing design and mobile bearing design ($P < 0.05$).

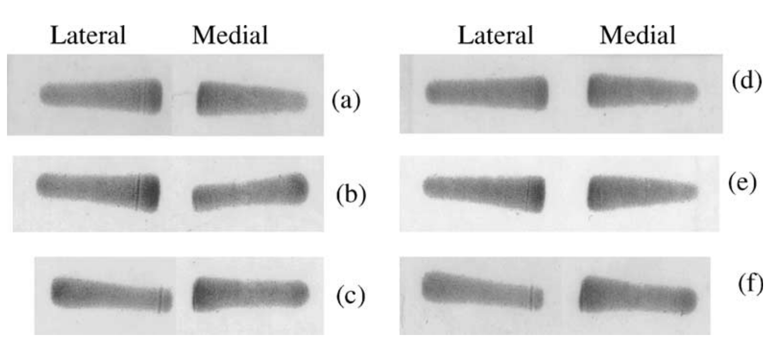

Fig. 3. The typical results of contact pressure distribution measured by Fuji prescale sensitive film. The malalignment conditions include the (a) neutral position; (b) medial translation 0.5 mm; (c) lateral translation 0.5 mm; (d) anterior translation 2 mm; (e) posterior translation 2 mm; and (f) external rotation 1° of the femoral component relative to the tibial component.

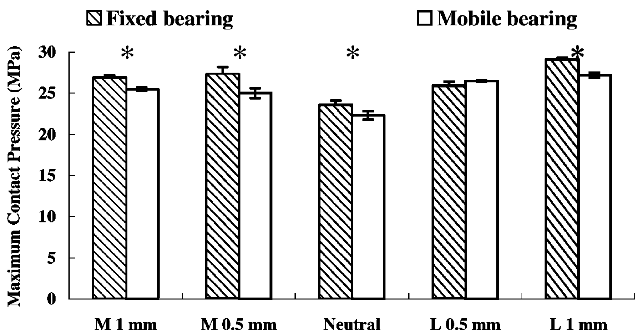

Fig. 5. MCPs in the medial (M) and lateral (L) maltranslation (mm) of femoral component relative to the normal contact alignment at 0° flexion; (∗) statistically different between fixed bearing design and mobile bearing design ($P < 0.05$).

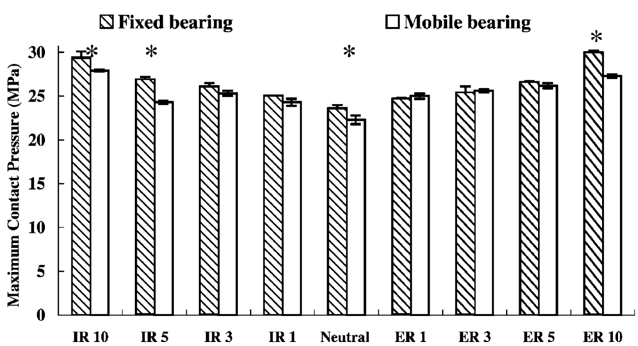

Fig. 6. MCPs in the IR and ER malrotation (degrees) of femoral component relative to the normal contact alignment at 0° flexion; (∗) statistically different between fixed bearing design and mobile bearing design ($P < 0.05$).

maltranslation, the greatest increase of MCP was 23.3% in the fixed bearing design and was 22.0% in the mobile bearing design. In IE malrotation, the difference of MCP between the mobile and fixed bearing was not significantly in the smaller malrotation angles (1° and 3°). However, when malrotation angles increased, the MCP of the fixed bearing design was significantly higher than the mobile bearing design. Comparing with the neutral contact alignment, the greatest increase of MCP in the fixed bearing design was 27.1% which was much higher than the mobile bearing design, 22.4% (Fig. 6). The MCP in the fixed bearing design was consistently higher than the mobile bearing design under malalignment situations.

4. Discussion

Mobile bearing knee prosthesis was designed to decrease the prevalence of prosthesis loosening and polyethylene wear (Goodfellow et al., 1986). It can also accommodate to surgical malalignment because of high mobility of the bearing element. When malalignment of prosthesis occurred, the loading distribution in the tibiofemoral joint would change, which may further alter stress distribution on the contact surface and soft tissues tension at knee joint. Therefore, to approach the actual conditions of knee prostheses in vivo and more objective to evaluate knee prostheses, the malalignment conditions should be taken into consideration (Liau et al., 1999; Liau et al., 2002).

In our previous study (Liau et al., 2002) using finite element analysis to calculate the ratios of MCP of tibiofemoral joint in three different curvature designs of fixed bearing knee prostheses under malalignment conditions relative to the normal contact alignment. One finite element modal (flat-on-flat design) was constructed base on U-knee system, which was also used in the current study. From finite element analysis, the greatest increase of MCP of tibiofemoral joint relative to normal contact alignment in fixed bearing U-knee prosthesis under a 3000 N compression load at 0° of knee flexion was 33.1% and 7.1% in the medial maltranslation (0.5 and 1.0 mm) and internal malrotation (1°, 3° and 5°), respectively. We also found that the greater the displacement of the femoral component moved medially, the greater the increase in MCP. Our results in current biomechanical test showed the same tendency with our previous finite element analysis.

Matsuda et al. (1998) measured MCP in one fixed and three specially designed mobile bearings Tricon II knee system (Smith & Nephew Richards, Memphis, TN, USA) under the normal contact alignment and 15° internal and external malrotations of the femoral component. The test conditions were subjected to a 3332 N compression loads at 0°, 30°, 60° and 90° of knee flexion. Their results showed that the greatest increase of MCP was much higher in fixed bearing design (178.1%) than the rotational sliding bearing design (25.0%) at 0° of flexion. In our study, the greatest increase of MCP at 10° malrotation was 27.1% in the fixed bearing design and was 22.4% in the mobile bearing design. The increase of MCP in fixed bearing design in Matsuda's study was much higher than our study. The main reason is that the Tricon knee prosthesis is a high conformity curve-on-curve design, but the U-knee system is a semiconformity flat-on-flat design. In a fixed bearing design, high conformity would increase MCP more significantly than low conformity design when malrotation of tibiofemoral joint occurs.

The smallest effect of malalignment on MCP is AP maltranslation because the applied load is almost even distributed on the medial and lateral parts of tibial component and the change of conformity between femoral component and tibial insert is less, which only occurs in the sagittal plane (Fig. 7(a)). When ML maltranslation of femoral component occurs, the applied load is uneven distributed on the medial and lateral parts of tibial component, which will increase the MCP more significantly in the part subjected to larger applied

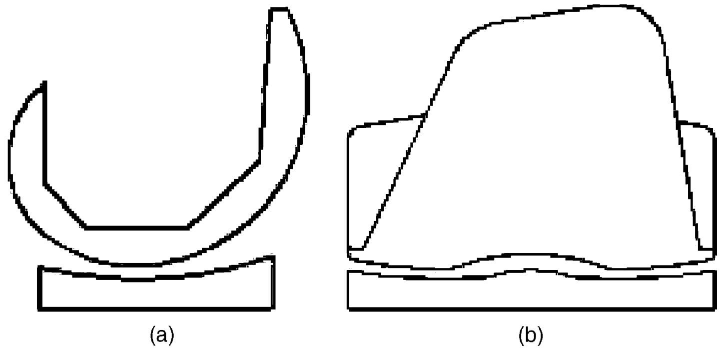

Fig. 7. An illustration of the U-knee system: (a) the sagittal view; (b) the coronal view.

load (Fig. 8). In the IE malrotation, the applied load is almost even distributed on the medial and lateral parts of tibial component. However, the curvature of U-knee system in the coronal plane is different to that in the sagittal plane. When malrotation of femoral component occurs, the conformity between femoral component and tibial insert will decrease in both coronal and sagittal planes, then the applied load will be concentrated in a smaller area. The concentrated load will increase MCP. The MCP always occurred near the middle part of the tibial baseplate on the frontal plane whether AP, ML or I/E malalignments were occurred, because the lowest point of the insert of the U-knee system is designed near the middle of tibial baseplate on the coronal plane (Fig. 7(b)). In this study, the MCP in the fixed bearing design was always higher than the mobile bearing design under malalignment situations. Mobile bearing knee prosthesis could reduce MCP because the polyethylene insert can self realignment by translating in both AP and ML directions and rotating internal and external on the metal tibial tray.

There are several limitations in this study. First, the nonhomogeneous of Fuji pressure sensitive film with 0.2 mm finite thickness inserted into the contacting surfaces may alter the original contact circumstance and introduce the discrepancies between the actual contact characteristics and the measured data (Liau et al., 2001).

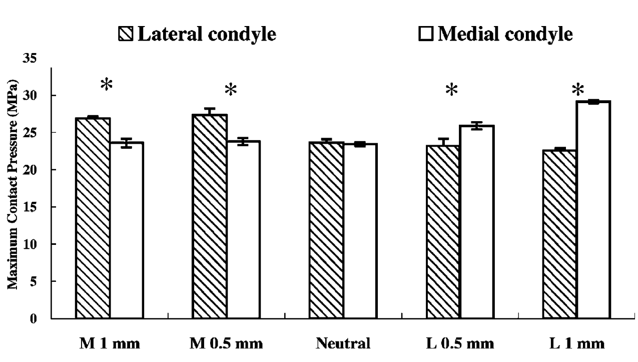

Fig. 8. The MCPs in the medial and lateral parts of tibial component in the medial (M) and lateral (L) maltranslation (mm); (∗) statistically different between medial and lateral tibial components.

Second, only a vertical compression load was applied to the tibiofemoral joint of knee prostheses at 0° of flexion. The effect of different flexion angles need to be further investigated. Third, most mobile bearing knee prostheses were designed in high conformity. However, the mobile bearing design in this study is a flat-on-flat semiconformity design. The flat-on-flat design may reduce the advantage of self-adjusting for surgical malalignment. Contact pressure in high conformity curve-on-curve design knee prostheses will be investigated in the future study.

5. Conclusion

The mobile bearing design has lower MCPs than the fixed bearing design when malalignment of the tibiofemoral joint of knee prosthesis occurs. The mobile bearing design offers the advantage of self-adjusting over the fixed bearing design to accommodate surgical malalignment.

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