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Visualisation of tibiofemoral contact in total knee replacement using optical device

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Abstract

An in situ optical visualization technique (OVT) has been developed to identify the tibiofemoral contact (TFC) area during prosthesis indentation. An artificial total knee replacement (TKR) with borosilicate glass femoral component has been reproduced similarly to the original one. The medial and lateral contact areas have been observed, located and measured by means of in situ OVT. Therefore, it was experimentally possible to ensure a good axial alignment of the femoral component and tibial polyethylene insert. In addition, experimental measurement for load–displacement curves became reproducible. Furthermore, the evolution of the medial and lateral TFC areas as a function of the normal load was established. Finally, this study has shown that the in situ OVT is a simple in vitro method that provides comparable results with well-known methods such as Fuji film technique.

Keywords: Tibiofemoral contact; Optical visualization; In vitro indentation; Biomechanics

1. Introduction

To investigate the performance of total knee replacement (TKR), the contact characteristics (contact area and contact stress) have been identified as important factors [1–11]. In the TKR, reduced contact area and excessive contact stress contribute to surface damage and to the high wear rate of the tibial polyethylene insert. Many parameters such as the conformity of component design, the contact alignment, the material properties of the component and the individual loading conditions can influence the contact characteristics.

Under static, quasi-static or dynamic in vitro and in vivo conditions, the control of the tibiofemoral contact (TFC) is highly important for long-life durability and high activity of TKR. Hence, if the TFC can be easily assessed, it would be possible to approve or disapprove implants design. Moreover, the relationship between the knee design and the knee kinematics would be well established. The wear of the tibial polyethylene insert could also be predicted.

Several techniques have been employed to evaluate the TFC: A digital tactile sensor has been employed under static and in vitro conditions [1–7]. The Fuji pressure sensitive film [2–6] and K-scan sensor [2,7] are currently the most popular tools for measuring the contact area and stress of the TFC. These techniques are limited to laboratory. They provide information regarding a modified contact by the presence of the stranger film. To investigate the effect of Fuji film on actual contact characteristics of artificial tibiofemoral joint, Liau et al. [5,6] have used finite element analysis. The authors have found that the measurement of contact area by using the film overestimated the actual contact area by 1.2–77% [5,6]. The insertion technique needs further investigations since it provides results depending on several parameters: nature and mechanical properties of Fuji film, applied load and finite element model. Furthermore, different designs in conformity of knee prostheses would influence the film's response.

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Recently, 2D/3D registration technique [8–11] was used to analyze the implants of TKR under dynamic and in vivo conditions. This technique determines the spatial position and orientation for metallic femoral and tibial component using X-ray fluoroscopy and computer-assisted design (CAD) model. X-ray fluoroscopy method provides information regarding the relative movement of radiopaque metallic components. The tibial polyethylene insert, which is radiolucent and does not appear on fluoroscopic images, was assumed to be fixed on the metallic tibial component and not to undergo any deformation or movement [11]. Therefore, this method is an approximate technique, whose complete data can not be obtained. Moreover, it doesn't permit to obtain the actual TFC.

In our previous studies [12,13], in situ microscopic observations of the contact area were performed during the fretting test. These observations were investigated through a cylindrical glass sample rubbed to a flat polymer using a microscope linked to a CCD camera and a video recorder. These works emphasized the importance of the in situ control of contact area in both the study of the fretting conditions [12] and the follow-up of polymer damage (particle detachment and third body behavior) [13].

The aim of the present study is to investigate the application of the in situ optical visualization technique (OVT) to provide useful information on the contact zone and the contact area of TKR in vitro conditions. This technique is applicable solely to an artificial TKR having transparent femoral component or transparent tibial insert.

2. Materials and methods

2.1. Used material

A HOWMEDICA TKR with Vitallium femoral component 6628-3 (MED.LG.-R) was used. Several UHMWPE (Ultra High Molecular Weight Polyethylene) inserts are compatible with this femoral component. A large size (9 mm, LG) and medium size (7 mm, MED) tibial inserts were selected. The UHMWPE is known for its superior biomechanical properties such as low friction coefficient against Vitallium, good resistance against wear, good biocompatibility and high toughness [14,15]. To reduce the cost of tested specimens, HDPE (High Density Polyethylene) plate which has similar mechanical and microstructural properties to UHMWPE [16] has been used.

2.2. Test equipment

To make contact between femoral and tibial components with a monotonous vertical load, an experimental indentation test apparatus (Fig. 1) was developed and mounted on a standard traction-compression machine. The tibial polyethylene insert (2) was clamped on the metallic support (1) which was fixed on the traction-compression machine frame. The femoral component (3) was rigidly mounted on a metallic holder (4). This holder was linked to the load cell (7) using an intermediate shaft (6) which allows the rotation around the horizontal axis (5) (perpendicular to

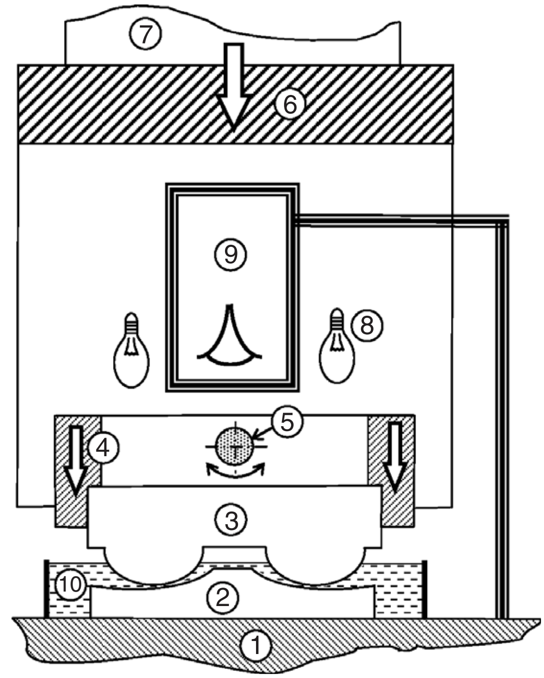

Fig. 1. Schematic of the indentation test apparatus: (1) metallic support, (2) polyethylene insert, (3) glass femoral component, (4) metallic holder, (5, 6) shaft, (7) load cell, (8) light, (9) video recorders or numerical camera, (10) colored liquid.

the traction-compression machine axis). This degree of freedom is necessary to avoid the application of torque on the load cell by equilibrating the medial and the lateral load. The load cell (7) was directly fixed on the crossbar of the traction-compression test machine. Indentation tests were performed at a constant displacement rate of 0.5 mm/min in a neutral position. These tests were also carried out by varying the normal load until 3000 N. For each test condition, a minimum of six samples were tested. The outputs of the displacement gauge and the load cell of the traction-compression test machine were continuously stored during loading and unloading. A corrected load–displacement curve was then obtained by accounting for the longitudinal strain arising from the compression of the test apparatus.

2.3. Femoral component manufacturing

In order to visualize the TFC area by the in situ OVT, artificial TKR with transparent femoral component was needed. Therefore, a borosilicate glass femoral component was manufactured similarly to the original Vitallium component as follows. First, a 3D computer model of the original Vitallium component was performed using an ordinate digitizer and a CAD tool. The impression of the femoral component was then machined in a metallic mold using a Computer-Aided Manufacturing (CAM) tool and a computer-controlled cutting machine. Finally, the thermo creep technique of the borosilicate glass was used to obtain the glass femoral component. The back face of the glass femoral component was flatted by polishing to minimize the optical distortion of contact area image. Since the glass Young modulus is much higher than the one of polyethylene (around 70 times), the glass femoral component was considered to be perfectly rigid such as the Vitallium component. Therefore, the response of artificial