Wear 332-333 (2015) 687–693

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

In-vitro and in-silico investigations on the influence of contact pressure on cross-linked polyethylene wear in total knee replacements

Sean T. O'Brien, Yunhua Luo, Jan-M. Brandt*

University of Manitoba, Winnipeg, MB, Canada

ARTICLE INFO

Article history:
Received 17 September 2014
Received in revised form
14 February 2015
Accepted 16 February 2015

Keywords:
Total knee replacement
Polyethylene wear
Contact pressure
Knee simulator
Computational wear simulation
Finite element simulation

ABSTRACT

Various conflicting trends have previously been reported for the influence of contact pressure on the polyethylene and crosslinked polyethylene wear of total knee replacements. In the present study, the influence of contact pressure on crosslinked polyethylene wear in total knee replacements was investigated using in-vitro knee simulator wear tests and in-silico computational wear simulations. Knee simulator wear tests were conducted under standardized and increased loading. The knee simulator wear test results were predicted using computational wear models with various contact pressure – wear trends to evaluate the accuracy of each approach. The knee simulator wear tests revealed the increase in loading (1.7 fold) to greatly increase crosslinked polyethylene wear (4.49 fold). The computational wear simulations revealed the wear model with the trend of linearly increasing wear with increasing contact pressure to result in improved agreement with the knee simulator results over the non-linear and contact pressure independent models. However, all of the computational wear simulations under-predicted the increase in wear caused by the increase in load. The results suggest that crosslinked polyethylene wear in total knee replacements may increase with increasing contact pressure and that the trends of pin-on-disk tests may not be directly applicable to total knee replacements with regard to contact pressure.

1. Introduction

Total knee replacements (TKRs) are projected to become increasingly implanted in younger, heavier and more active patients [1]. With younger patients also comes the objective of longer implantation periods in order to reduce the number of revision surgeries required in the lifetime of TKR patients. Longer implantation periods, younger, heavier and more active patients all contribute to increased tribological demand on TKRs. Despite the recent advancements in TKR bearing materials [2–5], wear particle induced osteolysis [6,7] may continue to limit the long term success of TKRs due to this increased tribological demand. Therefore, the design of TKRs with improved wear resistance may increase the long term success of these devices.

The effects of contact pressure on wear must be understood to enable the design of TKRs with improved wear resistance, as well as for the development of accurate computational wear models. Contact pressure has been demonstrated to have a complicated effect on polyethylene (PE) and crosslinked polyethylene (XPE) wear. Pin-on-disk (POD) tests have previously been utilized to investigate the effects of contact pressure on wear [8–12]. Some POD tests have demonstrated trends of initially increasing wear with increasing contact pressure, followed by decreasing wear with increasing contact pressure [9–12]. Meanwhile, other POD tests have demonstrated trends of decreasing wear with increasing contact pressure [8]. The reasons for these somewhat different trends are not currently understood. It is considered possible that, for POD tests which do not exhibit the initially increasing wear with increasing contact pressure trend, the peak wear rate (peak wear volume/million cycles) may have occurred at a contact pressure lower than the lowest contact pressure of the tests. These POD test trends may not be intuitive based on the wear of other materials which tend to consistently increase with increasing contact pressure [13].

The efficiency and simplicity of POD tests make POD testing an appealing choice for the investigation of the effects of contact pressures on PE and XPE wear. However, the contact and lubrication conditions of POD tests are different than those of a TKR. Therefore, it remains unknown whether these POD contact pressure trends are directly applicable to TKRs. The direct investigation of the effects of contact pressure on the wear of a TKR in a knee simulator would be of great value. However, to the authors' best knowledge, knee simulator wear tests conducted under a reference and increased vertical load, while keeping all other variables and kinematics constant, are not available in the literature. Clinical results regarding the effect of contact pressure on PE and XPE wear appear to be inconclusive. Several studies have suggested that increased body mass index may have a negative impact on clinical outcome [14–16], while other studies suggest that increased body mass does not

* Corresponding author.

http://dx.doi.org/10.1016/j.wear.2015.02.048
0043-1648/

negatively affect the clinical outcome [17–19]. Unfortunately, the effect of load and contact pressure on clinical wear is difficult to assess directly, as patients of increased body mass index may also have decreased levels of activity [20].

In-silico computational wear simulations can be used to predict the wear of a TKR with greatly increased time and cost efficiency over knee simulator wear testing [21]. Therefore, the increased efficiency of in-silico computational wear simulations may enable a wider range of design variables to be considered than is currently possible using only knee simulators. The ideal design process for TKRs with respect to wear may include the optimization of TKRs for the reduction of wear by in-silico computational wear simulation, followed by in-vitro knee simulator testing for final design verification. The effects of contact pressure on wear must be understood and incorporated into the computational wear model for the accurate simulation of wear. Currently existing computational wear models have utilized linearly increasing wear with increasing contact pressure trends [22–30], contact pressure independent trends [31,32], decreasing wear with increasing contact pressure trends [8,11] and a non-linear [21] contact pressure model which replicated the increasing and then decreasing wear with increasing contact pressure trends displayed by POD tests. It remains uncertain which of these contact pressure trends is the most relevant to TKRs.

The objectives of the present study were to investigate the effects of contact pressure on TKRs through in-vitro knee simulator wear testing and to evaluate the accuracy of in-silico computational wear predictions using various contact pressure – wear models.

2. Methods

2.1. In-vitro knee simulator wear tests

In-vitro knee simulator wear testing was conducted to evaluate the effect of increased contact pressure on TKR wear. The PFC-Sigma TKR (PFC-Sigma, Depuy Synthes, Warsaw, IN) was selected for the analysis to represent a modern TKR design. The PFC-Sigma includes a tibial insert comprised of GUR 1020 XPE sterilized using gamma irradiation with vacuum foil at 2.5–4 MRad to provide a moderately crosslinked XPE insert. This moderate level of crosslinking is typical of modern TKR designs [33]. TKR components of size 3 with a nominal XPE insert thickness of 10 mm were utilized. These particular TKRs had previously been used in a 10 million cycle (MC) knee simulator wear test [34], under the loading and displacement conditions of the ISO standard 14243-3 [35].

A six station displacement controlled AMTI knee simulator (AMTI, Waltham, MA) was utilized to conduct the knee simulator wear testing. The right bank of the knee simulator was utilized, which included three dynamic wear stations (R1–R3) and two load-soak stations (R4–R5). Each wear station was subjected to the flexion–extension, vertical loading, anterior–posterior motion and internal–external rotation of the ISO standard 14243-3 [35] (Fig. 1) or with increased vertical loading beyond the ISO standard. The load-soak stations were only subjected to the vertical loads and were used to account for the fluid absorption of the PE inserts. Therefore, the PE insert wear could be measured gravimetrically by subtracting the average change in weight of the load-soak stations from the gravimetric weight loss of each wear station PE insert.

Each wear station and load-soak station included a dedicated lubricant circulation system. The lubricant circulation system of each station included a peristaltic pump and a 500 ml heated reservoir which maintained a temperature of 37.5 °C. The peristaltic pumps circulated lubricant through the wear stations at an approximate rate of 100 ml/min. The lubricant was composed of bovine calf serum diluted with distilled water to a protein concentration of 17 g/L according to ISO 14243-3. Ethylenediaminetetraacetic acid was added (20 mM) to the lubricant to inhibit calcium deposits. Sodium azide was also added (0.2%) to the lubricant to inhibit microbial growth. All inserts were pre-soaked in the lubricant for six weeks prior to commencing the wear test to minimize the change in fluid absorption during wear testing.

A frequency of 1 Hz was used as the gait cycle frequency of all tests. Following each 0.5 MC cycle interval, each station was disassembled, the components were cleaned, the lubricant was replaced, and the PE inserts were weighed. Each PE insert was weighed using a high precision balance (XP205, Mettler-Toledo, Columbus, OH). Gravimetric measurements were converted to volume using an assumed PE density of 0.935 mg/mm^3 [33]. Linear regressions were utilized to analyze the steady-state wear rate of the PE insert of each wear station during each test. 95% confidence intervals were also calculated for the steady-state wear rate of the PE inserts of each test.

The first test implemented the ISO 14243-3 standard [35] for the loading and displacement conditions. The second test was conducted immediately after the first test and utilized the same components. The second test also implemented the stated ISO standard with the exception of the vertical load being increased 1.7 fold. Knee simulator wear tests are subject to experimental variability. Each test consisted of at least 1.5 MC or as many cycles as necessary to result in a wear rate 95% confidence interval of less than 20% of the wear rate value. The knee simulator wear rates for both the standard and increased loading tests were calculated based on the mean value of the slopes of linear regressions for each wear station.

2.2. In-silico computational wear simulations

In-silico computational wear simulations were conducted to analyze which contact pressure – wear trend resulted in the greatest agreement with the in-vitro results, as well as consider the predictive accuracy of in-silico computational wear simulations. Finite element simulations were conducted to analyze the contact interactions between the femoral component – XPE tibial insert and tibial tray – XPE tibial insert. The simulations were conducted using Abaqus Explicit (6.13, Simulia Inc., Providence, RI). Consistent with the in-vitro experiments, size 3 PFC-Sigma TKR components were used, with a XPE tibial insert of 10 mm nominal thickness. Three-dimensional computer-aided-design (CAD) models of the components were obtained from the manufacturer (Depuy-Synthes, Warsaw, IN). The femoral component and tibial tray were modeled as rigid bodies for computational efficiency. This simplification is expected to have an insignificant effect on the results, as the modulus of elasticity of the cobalt chromium alloy of these components is more than 300 times greater than that of the XPE tibial insert [33]. The tibial insert was modeled as a deformable body with a J_2-plasticity constitutive model which has previously been demonstrated to provide accurate results [36,37]. The appropriate loading and boundary conditions were applied to the femoral and tibial tray components [21,23,36] to replicate the loading and displacement conditions of ISO 14243-3 and the increased loading scenario from the in-vitro testing. The components were meshed using a hexahedral dominated mixed mesh of hexahedral and tetrahedral elements. Mesh densities were determined by convergence analyses.

The contact pressure and sliding displacement vector results of the finite element simulations were used to predict XPE wear using a previously developed wear model [21]. The implemented wear model features time dependent cross shear and energy dissipation wear prediction with consideration for tractive rolling. The wear model has previously been demonstrated to provide accurate wear prediction for POD and several knee simulator wear tests [21]. Three variants of the model were implemented, each of which utilized a different contact pressure – wear trend [21]. The first model (linear, M1) predicts linearly increasing wear with increasing contact pressure according to