The Knee xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

The Knee

Computational modelling of motion at the bone–implant interface after total knee arthroplasty: The role of implant design and surgical fit

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A R T I C L E I N F O

Article history:
Received 16 May 2016
Received in revised form 12 May 2017
Accepted 4 July 2017
Available online xxxx

Keywords:
Implant design features
Surgical resections
Saw blade error
Primary knee arthroplasty
Revision knee arthroplasty
Finite element analysis

A B S T R A C T

Background: Aseptic loosening, osteolysis, and infection are the most commonly reported reasons for revision total knee arthroplasty (TKA). This study examined the role of implant design features (e.g. condylar box, pegs) and stems in resisting loosening, and also explored the sensitivity of the implants to a loose surgical fit due to saw blade oscillation.
Methods: Finite element models of the distal femur implanted with four different implant types: cruciate retaining (CR), posterior stabilising (PS), total stabilising (TS) with short stem (12 mm × 50 mm), and a total stabilising (TS) with long stem (19 mm × 150 mm) were developed and analysed in this study. Two different fit conditions were considered: a normal fit, where the resections on the bone exactly match the internal profile of the implant, and a loose fit due to saw blade oscillation, characterised by removal of one millimetre of bone from the anterior and posterior surfaces of the distal femur. Frictional interfaces were employed at the bone–implant interfaces to allow relative motions to be recorded.
Results: The results showed that interface motions increased with increasing flexion angle and loose fit. Implant design features were found to greatly influence the surface area under increased motion, while only slightly influencing the values of peak motion. Short uncemented stems behaved similarly to PS implants, while long canal filling stems exhibited the least amount of motion at the interface under any fit condition.
Conclusion: In conclusion, long stemmed prostheses appeared less susceptible to surgical cut errors than short stemmed and stemless implants.

1. Introduction

Micromotion of the tibial bearing component and failure of the tibial tray have been examined extensively using in vitro and in silico techniques [1–5]. However, there is a current lack of corresponding studies that deal with micromotion of the femoral component, despite the fact that the difference between the number of revised tibial and femoral components as a result of aseptic loosening is <3% [6]. While it is possible that a small percentage of femoral component revisions may occur in parallel to revision of a loose tibial component (to ensure conformity), it is unlikely that this factor alone would account for the majority of femoral components revised due to aseptic loosening. The reported trends with respect to loosening [6,7], and the increasing

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http://dx.doi.org/10.1016/j.knee.2017.07.003
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number of revision total knee arthroplasty (TKA) performed each year [8] suggests that aseptic loosening of the femoral component has the potential to become a more serious clinical issue.

For ethical reasons, little information exists on the acceptable level of interfacial motion which leads to bone ingrowth vs. fibrous tissue formation and eventual loosening following TKA in humans. However, prior studies have attempted to extrapolate the upper and lower bounds of motion based on canine models [9,10]. Pilliar et al. reported that motions in excess of 150 μm were disruptive to osseointegration at the prosthesis bone interface and led to the formation of fibrous tissue [9]. A subsequent more comprehensive in vivo study, again using a canine model, placed the lower bound of motion for this fibrous tissue phase at 40 μm [10]. On the other hand, low levels of motion at the bone implant interface (<40 μm) may be beneficial in promoting bone ingrowth into the prosthesis, and increase stability through a strong bond between prosthesis and bone [11,12].

Early indications of loosening and implant failure in humans are observed clinically by tracking changes in the position and orientation of the implant over time through examination of radiographs or through more specialised techniques such as radio-stereo-photogrammetric analysis (RSA) [13–16]. However, such techniques are typically limited to tracking values of inducible motion or permanent migration that exceed 100 μm [16–19], and are unable to resolve the relatively small interfacial motions (40–100 μm) that play a key role in particle-induced osteolysis and aseptic loosening of the implant [14].

It is recognised that the fixation method (cemented or uncemented) and implant configuration (e.g. stemmed or stemless) can exert a large influence on the global motions between bone and implant [20–23]. Recent studies have suggested that implant design features, such as size and placement of distal femoral pegs [24], anteroposterior slope of the femoral component [25], and angle of fit of the implant [26], may also play a role in the long-term survival of the prosthesis.

Another factor that may influence clinical outcomes is saw blade oscillation. Undesirable motion of the saw blade during an operation can lead to errors in femoral cuts [27–29], where displacement of the free end of the saw blade is a function of blade thickness (e.g. increasing blade thickness reduces displacement) [29]. Out of plane motion of the saw blade in combination with displacement of pinned cutting blocks during surgery has been found to result in surgical cut errors of the range of 0.8–1.2 mm [27,28,30], leading to a less than optimal positioning of the prosthesis and potentially compromising the long-term survival of the implant.

As a result, the aims of the current study were:

- To determine the influence of implant features, such as pegs, condylar box sections, and stems, on motion at the bone–implant surface for an uncemented femoral component.
- To examine which of these implant configurations are more resistant to a loose fit scenario.

It was hypothesised that implant design features play a key role in determining the magnitude and distribution of motion at the bone–implant interface, and that motions for all implants would increase in the presence of a loose fit.

2. Materials and methods

2.1. Geometry

This study used a virtual representation [31] of the large left fourth-generation composite femur (Sawbones; Pacific Research Laboratories, Vashon, Washington) implanted with four different implant types, as shown in Figure 1: (a) a cruciate retaining implant (CR), (b) a posterior stabilising implant (PS), (c) a total stabilising implant with short stem (TSSS) (12 mm × 50 mm), and (d) a total stabilising implant with long stem (TSLS) (19 mm × 150 mm) from the Triathlon® series product line (Stryker®, Newbury, United Kingdom). Computer-aided design software (Autodesk Inventor™ 2010, Autodesk Inc., San Rafael, CA) in conjunction with surgical template measurements was used to develop three-dimensional (3D) models of each femoral implant that was investigated, and to carry out surgical resections on the femur for virtual implantation.

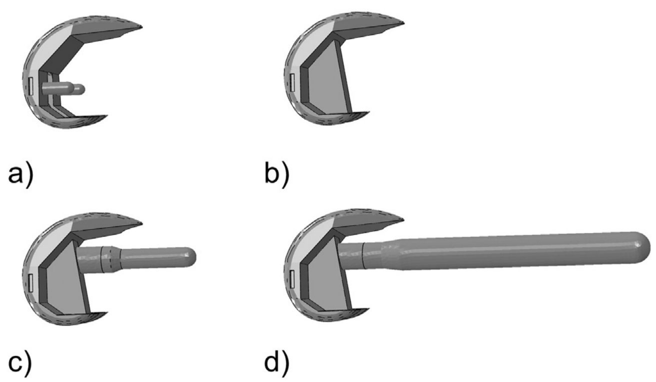

Figure 1. Computer-aided design model of a) a cruciate retaining implant, b) a posterior stabilising implant, c) a total stabilising implant with 12 mm × 50 mm stem, and d) a total stabilising implant with 19 mm × 150 mm stem.