Journal of Biomechanics 46 (2013) 1387–1391

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Validation of the in vivo volumetric wear measurement for total knee prostheses in model-based RSA

E.A. van IJsseldijk [a,*], B. Lebel [b], B.C. Stoel [c], E.R. Valstar [a,d], S. Gouzy [b], C. Vielpeau [b], B.L. Kaptein [a]

[a] Biomechanics and Imaging Group, Department of Orthopaedics, Leiden University Medical Center, The Netherlands
[b] Department of Trauma and Orthopaedic Surgery, Centrale Hospital Universitaire Caen, France
[c] Department of Radiology, Leiden University Medical Center, The Netherlands
[d] Department of Biomechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering, Delft University of Technology, Delft, The Netherlands

ARTICLE INFO

Article history:
Accepted 26 February 2013

Keywords:
Total knee arthroplasty
Polyethylene wear
Image-based measurements
Model-based RSA

ABSTRACT

Implant failure related to polyethylene wear remains an important issue in total knee arthroplasty. Polyethylene wear is usually assessed in vivo by measuring the remaining insert thickness on X-ray images of the knee. To reflect the amount of wear debris more accurately, a 3-dimensional overlap measurement has been suggested, which is based on implant component models which are matched on calibrated stereo X-ray images using model-based roentgen stereophotogrammatic analysis. The goal of this study was to determine the influence of pose estimation, insert thickness deviation and variation in the femoral-tibial contact location on the accuracy and precision of the measurement using simulations and a phantom experiment.

We found that the pose estimation was the largest source of variation. The 95% prediction interval varied between 111 and 283 mm^3, which is approximately 100–200% of the detected volumetric wear. Insert thickness variation resulted in prediction intervals of 74–174 mm^3. Variation of the femoral-tibial contact location in the phantom experiment gave a prediction interval of 40 mm^3. Large differences in the detected wear volume were found for different flexion angles. At most 56% of the true wear volume was detected (129 of 230 mm^3, 30° of flexion).

In summary, both the accuracy and precision of the volumetric wear measurement were low. The prediction interval of the volumetric wear measurement is at least as large as the measurement outcome itself. This is an important limitation to the applicability of the volumetric wear measurement in clinical practice and further clinical validation is required.

1. Introduction

Polyethylene (PE) wear is an important cause of implant failure of total knee arthroplasty (TKA), as it can lead to instability and aseptic loosening (Naudie et al., 2007; Sharkey et al., 2002; Sundfeldt et al., 2006). Therefore, an accurate and precise method is required to assess the in vivo progression of PE wear in vivo, which can be used to predict instability and loosening so as to initiate a timely intervention.

The current method to assess the progression of PE wear in vivo is measuring the minimum distance between the femoral condyles and the tibial plateau using radiographic and fluoroscopic imaging (Collier et al., 2003; Duryea et al., 2001; Miller, 2005; Sanzén et al., 1996; van IJsseldijk et al., 2012). However, this 2-dimensional measurement does not reflect the total volume of wear debris that has been released. Therefore, Gill et al. (2006) presented a method to measure the in vivo wear volume using 3-dimensional (3-D) geometric models of the implant components, by estimating their 3-D poses (positions and orientations) from stereo X-ray images and calculating the overlap volume with the insert.

For the most part the accuracy and precision of this measurement method have not been validated. The goal of this study was to determine the influence of important sources of variation on the accuracy and precision of the volumetric wear measurement. Amongst others, these depend on the 3-D pose estimation and deviations in the original insert thickness as a result of the manufacturing process. Simulation studies were conducted in which the isolated influences of these sources on the measurement were determined.

In practice, wear is often caused by the sliding motion of the femoral component relative to the insert. Therefore, the accuracy

* Corresponding author. Biomechanics and Imaging Group, Department of Orthopaedics, Leiden University Medical Center, Room J9-127, P.O. Box 9600, 2300 RC Leiden, The Netherlands. Tel.: +31 71 5265358; fax: +31 71 5266743.
E-mail address: e.a.van_ijsseldijk@lumc.nl (E.A. van IJsseldijk).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.02.021

and precision of the measurement will also relate to the flexion angle at which the measurement is conducted and the variation in the femoral contact location on the insert. A phantom experiment was done to determine the influence of these sources, using inserts with abrasive wear.

2. Materials and methods

The volumetric wear measurement was conducted based on image pairs that were acquired using a röntgen stereophotogrammetric analysis (RSA) setup with the calibration box in vertical orientation (Kaptein et al., 2003). The image pairs were analyzed with model-based RSA software (v3.32, Medis Specials, Leiden, The Netherlands) to estimate the poses of the prosthesis components, which are described with triangulated surface models (Kaptein et al., 2003). Since the insert component does not produce clear image contours, its pose was derived from the pose of the tibia model, as they have a fixed spatial relationship.

Volumetric wear was detected by calculating the 3-D overlap region between the femoral and insert component models. A regular 2-D grid was defined (0.8×0.8 mm cell size) that coincided with the tibial plateau. For each grid point the overlap distance between the femoral component's surface and the insert surface was calculated. The wear volume was computed using a numerical integration of these distance values based on Simpson's rule.

3. Simulation experiments

The influences of pose estimation and insert thickness deviations were determined in simulation experiments. We calculated the difference in the detected volumetric wear as a function of the relative pose of the femoral component with respect to the tibial component. This pose is expressed as $p=(x, y, z, \alpha, \beta, \gamma)^T$, where x, y, and z are the medial, caudal and anterior position parameters and α, β and γ are the corresponding Euler angles (Fig. 1).

The experiments were repeated with eight initial poses $p_{0,j}$ ($j=1\ldots8$), which were obtained from eight RSA data of patients with size 4 Triathlon PS total knee prostheses (Stryker Europe, Raheen, Ireland).

The effect of pose estimation error was computed in a Monte Carlo Simulation. For each initial pose the detected volumetric wear $w_{0,j}$ was calculated and 500 new poses were generated as $p_{i,j}=p_{0,j}+d_{i,j}$. The pose errors $d_{i,j}=(d_{xi,j}, d_{yi,j}, d_{zi,j}, d_{\alpha i,j}, d_{\beta i,j}, d_{\gamma i,j})^T$ were drawn from a normal distribution with zero mean and a standard deviation (SD) of (0.085 mm, 0.085 mm, 0.22 mm, 0.343°, 0.414°, 0.23°)^T. These SDs were derived from a clinical validation study (Kaptein et al., 2007). For each pose the detected wear volume $w_{i,j}$ and measurement error $e_{i,j}=w_{i,j}-w_{0,j}$ were calculated.

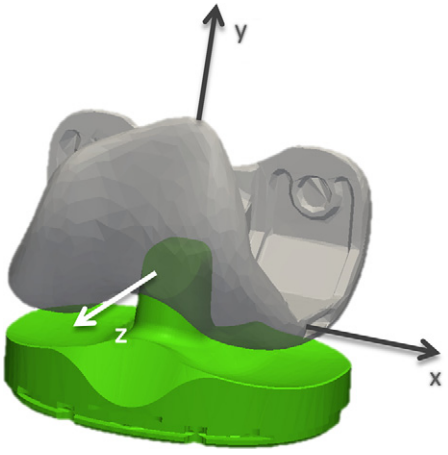

Fig. 1. The coordinate system that was used in the simulation study.

The variation in insert thickness was simulated by varying the caudal position parameter of the relative pose with Δd, resulting in $p_j=p_{0,j}+(0, \Delta d, 0, 0, 0, 0)^T$. The parameter was varied between +0.12 mm and −0.12 mm, which is in the range of the 95% prediction interval assuming that the thickness among insert components of the same type and size vary with an SD of 0.06 mm (Collier et al., 2003; Edwards et al., 2002; Psychoyios et al., 1998).

4. Phantom experiment

The phantom experiment was conducted to assess the influence of variation in the femoral-tibial contact location and the knee angle to the volumetric wear measurement. We used a knee prosthesis (size 4 Triathlon PS) with inserts containing a predefined wear pool and determined how accurately these wear pools could be reconstructed by the volumetric wear measurement.

The wear in the inserts was designed in SolidWorks CAD software (Dassault Systemes, Paris, France). A femoral component model (size 5 Triathlon PS) was placed in bearing contact with the insert model and subsequently moved downward (into the insert). This produced a 3-D overlap volume between the models, which was removed from the insert model. Different sizes and shapes of the wear pool were created ($N=6$) by varying the flexion angle of the femoral component and the distance over which it was moved into the insert. We used a larger size femur component to simulate wear caused by the sliding motion of the femoral component. The physical insert was manufactured by a computer controlled milling device (Stryker Europe, Raheen, Ireland). We selected an insert for which the femoral-tibial contact location was consistently found inside the wear pool in the volumetric wear measurement (see Fig. 2). The data of all other inserts is presented in Appendix A.

A total knee prosthesis was assembled with the selected insert placed in the tibial component. For analysis and pose estimation 3-D scans of the insert, femoral and tibial components were generated by means of reversed engineering (Introtech, Nuenen, the Netherlands). Based on the insert scan, the shape and volume of the true (predefined) wear pool were determined.

This especially prepared prosthesis was fixed into sawbones. The tibia sawbone was placed in a vertical position on a tripod. The femur sawbone could be positioned on top of the tibia in any flexion angle, as a 7 kg balancing weight was used to stabilize the set-up (see Fig. 3). The sawbones were placed in a horizontally oriented RSA imaging setup. Five consecutive RSA image pairs were obtained for three flexion angles (0°, 30° and 60°) resulting in 15 image pairs totally. Before obtaining each of these image pairs, the femoral component was remounted in such a position that the predefined flexion angle was set (verified by a

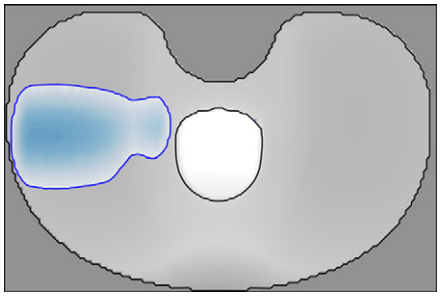

Fig. 2. Illustration of the predefined wear pool (size=230 mm^3). The shading intensity of the blue area corresponds to the depth of the wear pool with respect to the insert surface. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)