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Introduction
Introduction

1-1 Osteoarthritis of the knee

Osteoarthritis (OA) is a multi-factorial joint disease characterized by progressive degeneration of cartilage tissue thickening of the joint’s subchondral bone resulting in a painful and stiff joint with decreased limited mobility [1, 2]. Osteoarthritis is a disease on its own, but can also occur secondary to an inflammatory disease like rheumatoid arthritis, post-traumatic or after congenital or acquired limb deformities.

In 2011, approximately 594,000 Dutch inhabitants suffered from knee OA, which is approximately 4% of the total population [3]. Knee osteoarthritis affects especially elderly patients. In the Netherlands, the registered prevalence of this disease for patients over the age of 65 years was 6.4% and 11.2% for men and women respectively [3]. This is a major health care burden, resulting in 1.11 billion euros for the direct and indirect healthcare costs of osteoarthritis in the Netherlands alone in 2011. This is 1.2% of the total annual Dutch healthcare costs [4].

Due to an aging population and longer life expectancy the prevalence of knee osteoarthritis is increasing. Moreover, since obesity – which is a risk factor for osteoarthritis – is ever more present in our society, more and younger patients will be affected by osteoarthritis [5-9].
1-2 Total Knee Arthroplasty

Total Knee Arthroplasty (TKA) is an effective treatment for endstage symptomatic osteoarthritis [10, 11]. TKA is a surgical procedure in which the knee joint is replaced by a prosthesis consisting of a femoral component, a tibial component, a polyethylene insert facilitating the articulation between the femoral and tibial component and, in some cases, a patella component (Figure 1-1).

![Illustration of a knee prosthesis and its components.](image)

Performed widely from the 1970’s, the procedure is well-established as a successful treatment in relieving pain and restoring joint function for patients with end stage osteoarthritis [11]. In general, an incision is made longitudinally across the knee, the joint capsule is opened and the patella (knee cap) is exposed by rotating it to the lateral side. Further dissections are made until the distal femur and proximal tibia are sufficiently exposed. The prosthesis’ components are fixated to the corresponding bones. Before this can be done, bone has to be removed so that the artificial
components have a close fit. Fixation of the components can be obtained either by applying bone-cement or by bone ingrowth.

Many different types and designs of knee prostheses are available, like posterior stabilized types, cruciate retaining types or rotating platform types. These types were developed to improve the kinematics or the stability of the prosthesis. Depending on the prosthesis type, the cruciate ligaments are resected or retained, the patella is resurfaced or not or additional collateral ligament balancing is required. As for rotating platform tibia components, this design allows for higher tibiofemoral conformity without undue kinematic constraint. Even though TKA is generally successful, implant failure remains a significant problem. National registries report a failure rate of 5% to 10% at 10 years after the initial surgical procedure, indicating revision surgery was required \[9, 12, 13\]. Revision surgeries are extensive procedures with higher intra- and post-operative risks. Moreover, revision TKAs have a higher risk of revision (i.e. re-revision) and lower patient satisfaction compared to primary TKAs \[14\]. Altogether, the impact of implant failure on patients and healthcare costs is substantial \[12\].

In line with the increase in the number of patients suffering from osteoarthritis of the knee, the incidence of TKAs is also expected to increase. Therefore, the impact of implant failure will increase as well. As implant failure is more frequent for younger, more active patients and the prevalence of TKAs for younger patients increases \[14, 15\], the impact of implant failure is aggravated further. In order to reduce patient consequences and the financial burden of TKA procedures, reduction of the number of implant failures is an important topic in both clinical and technical research.

**1-3 Polyethylene wear**

The insert of a TKA is made of ultrahigh molecular weight polyethylene, which is designed to withstand the sliding and rolling articulation of the femoral component in the daily use of the prosthesis. However, wear of this component occurs due to various factors such as e.g. excessive forces during articulation, poor quality of the polyethylene material and poor alignment of the implant components increasing the load on articulating surfaces \[16-18\].
Wear particles ranging in size between 0.1 microns to 0.5 millimeter are released in the wear process. Especially the smaller particles can cause a local inflammatory reaction, which is associated with bone resorption around the TKA resulting in osteolysis and eventually aseptic loosening of the prosthesis[19, 20]. Aseptic loosening is an important failure mechanism as it is related to one out of every four revisions[21, 22].

Besides, TKA failure can occur for severe wear cases when metal to metal contact between the prosthesis elements occurs, resulting in an irreversibly damaged and non-functional prosthesis.

**1-4 Relevance of measuring wear**

It has been shown that the rate at which the remaining insert thickness decreases can predict TKA failure[23, 24]. For this reason, an accurate and precise method is required to assess the progression of polyethylene wear *in vivo*, which can be used to predict (future) instability and loosening and thereby support clinical decision making as to initiate a timely intervention or to decide which patients should be monitored more intensively. Timing is very important to minimize the burden of surgery for both the patient and the surgeon[12]. On the one hand, the surgical procedure should not be performed too soon as to prevent unneeded risks for patients. On the other hand, postponing the revision surgery may lead to an inferior outcome in case of high wear rates, due to the progressing osteolysis (reducing the bone stock available) and the increased inflammation related to wear debris.

A second application for an accurate and precise wear measurement is to evaluate the wear resistance of (new) prosthesis designs[25]. Wear characteristics of new prosthesis designs are currently assessed with knee simulator studies before market introduction. These simulator studies apply repetitive loads and motion to the prosthesis based on models of daily patient activity, yet they are limited in incorporating patient-specific effects and events such as extreme usage or simple missteps[16, 26]. An accurate and precise measurement of polyethylene wear *in vivo* is therefore also required to monitor the quality of new and existing prosthesis designs.
1-5 Wear measurement techniques

In current clinical practice, weight-bearing planar radiographs are the clinical standard for the assessment of wear in vivo[27, 28]. In these images, the remaining polyethylene insert thickness is estimated using the minimum joint space width (mJSW) measurement, in which the apparent distance between the metal tibial tray and the femoral condyles is assessed [27, 29-31]. An example of an image with these reference objects is shown in Figure 1-2.

![AP radiograph of a TKA with arrows indicating the lowest point of the femoral condyle (A) and the tibial tray (B), which are the reference points to assess the remaining insert thickness.](image)

The conventional mJSW method is subject to parallax errors that occur when the metal tibial baseplate surface is not optimally aligned with the X-ray beam during
sequential radiographic assessments. Moreover, some design features such as a metal rim require manual adjustments of the conventional mJSW measurement method, rendering the method sensitive for human errors. Measurement errors of up to 2 mm are not exceptional and multiple follow-up visits are required to obtain a reliable estimation of the wear rate [28, 29, 31]. These errors seriously limit the application of this measurement method for the purpose of reliably monitoring patients or evaluating implant designs.

1-6 Model-based wear measurement

Radiographic measurement accuracy and precision can be improved by applying model-based techniques. Such techniques incorporate prior information of three-dimensional (3D) object geometry and are applied to enhance clinical decision making or surgical accuracy by using computer-guided navigation. Model-based techniques are also applied in Roentgen Stereophotogrammetric Analysis, a method used to predict implant loosening after TKA or Total Hip Arthroplasty [32-34]. Accuracy and precision of 3D pose reconstruction have proven to be very high for these model-based techniques, therefore rendering them pre-eminently suitable for in vivo wear measurements [32].

The application of model-based techniques to the mJSW measurement has several advantages. Measurements applied in 3D are less susceptible to parallax errors than direct measurements in projection images of standard radiographs. Moreover, these techniques can improve signal-to-noise ratio because more image information is used when matching complete components compared to selecting a single image point or image edge. Last, using 3D models provides additional measurement possibilities, such as the location of the mJSW.

The model-based mJSW measurement can also be used to improve the mJSW measurement for the natural knee, where it is used to assess the progression of osteoarthritis [2, 35]. In this case, the 3D models should be capable of matching the patient-specific tibial and femoral shapes. This can be achieved by using deformable models that are able to match a variety of shapes and use smart fitting criteria to match only the desired shape. One of these models is the statistical shape model
which uses a-priori knowledge from a training set to fit unseen shapes based on their plausibility. This model type has proven successful in matching shapes of the natural knee based on the limited information available in projection images [36-38].

The use of model-based techniques also introduces new challenges. Apart from the need for accurate 3D (prosthesis) models, it requires a 3D reconstruction in which the spatial relationship between the projection image and the 3D model is established. To accomplish this, reliable information on the image acquisition process should be available, such as the original focus (camera) position with respect to the image, the image pixel size and the image magnification. In case this information is missing or unreliable, the precision of positioning the 3D models can drop quickly.

Although model-based techniques have been applied for mJSW measurements, the accuracy and precision of these techniques have not been validated or validation has been restricted to individual prostheses or other imaging modalities such as fluoroscopy and calibrated stereo imaging [30, 39-43].

1-7 Aim of this thesis

The aim of this work is to improve the accuracy and precision with which mJSW measurements can be conducted in medical imaging. Hereto, this thesis focusses on the development, validation and clinical application of model-based mJSW measurements for the natural knee and TKAs. For TKAs the measurement is applied for both stereo-images and standard radiographs.

1-8 Structure

Chapters 2 to 4 focus on the development and validation of polyethylene wear measurements for TKAs using calibrated stereo-images and 2D-3D matching of exact models. In Chapter 2 the accuracy of the mJSW method using model-based RSA is validated in a phantom study using different TKA designs. In Chapter 3 the differences in mJSW measurement between weight-bearing and non-weight-bearing stereo images are assessed. Alternative to the mJSW measurement, polyethylene wear can also be estimated using the wear volume. In Chapter 4 the precision of
this volumetric wear measurement is analyzed by using both a phantom experiment and simulation studies.

Chapter 4 and 5 focus on the validation of the mJSW measurement in standard AP radiographs (i.e. mono images). In Chapter 4 a phantom study is used to perform this validation, which is equivalent to Chapter 1 for stereo-images. Ultimately, in vivo data are the most reliable basis to validate a measurement for clinical practice. In Chapter 5 a retrieval study is done to validate the measurement, in which the insert thickness measured in pre-revision images is compared to the actual insert thickness measured of the retrieved tibial inserts after revision.

Chapter 6 and 7 turn towards alternative model-based measurement techniques. In Chapter 6 the application of a volumetric wear measurement for knee prosthesis is considered and in Chapter 7 model-based techniques are applied to measure joint space narrowing in the natural knee. The accuracy and precision of the mJSW measurement of the knee using a Statistical Shape Model is compared to a conventional automated mJSW measurement.

Finally, Chapter 8 provides a general discussion and reflection on the improvement of the accuracy and precision with which mJSW measurements can be conducted in medical imaging. Also, directions for future work are described.

REFERENCES


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