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Measuring the minimum joint space width in total knee arthroplasty by RSA
Measuring the minimum joint space width in total knee arthroplasty by RSA

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Abstract

Introduction
Measuring the minimum joint space width (mJSW) in total knee arthroplasty (TKA) in Roentgen Stereophotogrammetric Analysis (RSA) studies provides valuable information on polyethylene wear, a leading cause for TKA failure. Most existing RSA studies use non-weight-bearing (NWB) patient positioning. The latter may compromise mJSW measurements due to knee laxity with subsequent non-contact between the TKA components. We investigated the difference in mJSW between weight-bearing (WB) and NWB images and the association with mediolateral (ML) knee stability.

Methods
23 TKAs from an ongoing RSA study were included. At one-year follow-up, WB and NWB RSA examinations were obtained and the ML stability was evaluated. For each examination the mJSW and femoral-tibial contact locations were measured. A linear regression model was used to analyze the association between the mJSW difference (NWB – WB) with the ML stability and contact locations.

Results
The mean mJSW difference was 0.28 mm medially and 0.20 mm laterally. 4 TKAs had medium (5 - 9 deg) and 19 TKAs had high (< 5 deg) ML stability. A higher mJSW difference was found for TKAs with medium stability (0.36 mm, p = 0.01).

Conclusion
In conclusion mJSW measurements in existing (NWB) RSA studies are influenced by knee laxity, but may still provide information on wear progression based on TKA with high ML stability. Because of the difference in contact point locations between WB and NWB positioning and the resulting difference in mJSW, a direct comparison between mJSW from WB and NWB data is not possible.
4-1 Introduction

Polyethylene (PE) wear is a leading cause for failure of total knee arthroplasties (TKAs)\cite{16, 20, 22}. The impact of PE wear is expected to increase further as the incidence of TKAs increases because of our aging and increasingly obese population\cite{5, 11, 54}. In addition, TKAs are applied more often in younger patients that have a more active lifestyle than older patients\cite{6, 11}.

Currently, the PE wear of new implant designs or implant materials is evaluated with in vitro knee simulator studies before market introduction\cite{66-68}. These studies do not incorporate the effect of patient specific and surgery specific factors to PE wear\cite{69}. This can lead to unforeseen complications. Alternatively, PE wear can be assessed \textit{in vivo} by measuring the minimum joint space width in radiographs. However, studies using these measurements are uncommon, which may be related to the low precision of conventional \textit{in vivo} wear measurements. Errors up to several millimeters have been reported and obtaining sufficient power is laborious\cite{28}. For example, to distinguish a difference of 0.2 mm in a clinical study approximately 250 patients would be required (2-sided power calculation, SD = 1 mm, alpha = 0.95).

Model-Based Roentgen Stereophotogrammetric Analysis (MBRSA) is an imaging and analysis technique which is known for its high accuracy in measuring migration of implants, which is used as a predictor for survival of knee prostheses\cite{44, 46, 70}. Several studies showed that techniques such as MBRSA can also be used to measure PE wear based on mJSW assessments\cite{43, 71}. We developed and validated such an mJSW measurement for MBRSA in a previous study\cite{72}. Now, this measurement technique can be applied to previous RSA studies on TKA migration, potentially providing information on wear progression.

In most of these RSA studies, however, images were acquired with a supine, non-weight-bearing patient position whereas the joint is loaded in radiographs that are used for conventional wear measurements. Literature states that weight-bearing positions are required for reliable \textit{in vivo} wear assessments in TKA\cite{27, 28, 73, 74}. In supine position, the femoral and tibial components may partially lose contact (due to laxity of the joint), causing the measurement to differ from the actual insert
thickness. This requirement has never been fully validated for knee prostheses, while for hip prostheses no difference in wear measurements between weight bearing and non-weight bearing images was found [75]. In case the measurement can detect PE wear progression in supine RSA images, ample data would become available from a multitude of clinical evaluation studies of TKA where successive supine X-rays were made for other purposes.

The primary aim of this study is therefore to determine whether the mJSW measurement differs between weight-bearing and non-weight-bearing positions. A secondary aim is to determine whether this mJSW difference can be related to knee laxity. This is analyzed by comparing TKAs with different mediolateral stability. We hypothesize that a lower mediolateral stability (thus a higher knee laxity) results in larger difference in the mJSW measured in WB and NWB positions.

4-2 Methods

4-2-1 Data
RSA image pairs and knee stability data were analyzed for 23 patients in an ongoing prospective RSA study conducted in ‘het Langeland Ziekenhuis’ (Zoetermeer, the Netherlands). All patients received a Stryker Triathlon Posterior Stabilized (PS) fixed bearing knee prosthesis. The cohort consisted of 7 males (30%) and 16 females (70%) and aged between 50 and 83 years (median 63 years). All patients gave informed consent to participate in this study.

At the one-year follow-up evaluation, RSA examinations were done in both a standing, weight-bearing (WB) and supine, non-weight-bearing (NWB) patient position. The mediolateral (ML) stability of the TKA was evaluated in degrees. TKAs were classified as having high stability (< 5 deg) or medium stability (5-9 deg). For the RSA examination in supine position a calibration box (Carbon box, RSA Core, dep orthopaedics, LUMC, the Netherlands) was mounted beneath the examination table [32]. For the examination in standing position, this calibration box was positioned vertically. The stereo images were acquired digitally using one mobile X-ray system (Siemens Mobilette, Siemens AG, Munich, Germany) and one in-room X-ray system (didi-series, Philips, Eindhoven, The Netherlands). The images had a pixel spacing of 0.2 by 0.2 mm.
All RSA analyses were carried out at the Leiden University Medical Center (dept Orthopeadics). 2D/3D registration was applied to the stereo images to reconstruct the position and orientation of the femoral and tibial components. This registration was done with model-based RSA software (RSAcore, dep orthopaedics, LUMC, the Netherlands) based on a standardized RSA analysis. This analysis consists of the consecutive steps of image calibration, edge detection and 2D-3D registration based on triangulated surface models using edge matching\cite{17,76}. For the femoral component computer aided design (CAD) models were used which were obtained from the manufacturer. The tibial models were reverse engineered (RE).

4-2-2 mJSW measurement

For all 46 RSA examinations ((WB + NWB) x 23 TKAs) the mJSW and the contact location of the medial and lateral condyles were measured. The mJSW is defined as the minimum distance between the metal tibial tray and the femoral condyle. The contact location is expressed in tibial tray coordinates $x_{AP}$ and $x_{ML}$ (Figure 4-10).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{tibial_component.pdf}
\caption{Top view of a tibial component with the coordinate system used to specify the contact location with respect to the tibial tray. The origin of the system coincides with the center of the bounding box of the insert. An example vector $x$ is drawn with the AP and ML components indicated.}
\end{figure}
4-2-3 Analyses

We calculated the difference in mJSW and contact location coordinates ($d_{AP}$ and $d_{ML}$) between each weight-bearing and non-weight-bearing examination (NWB – WB). For $d_{AP}$, this difference was calculated based on the absolute AP coordinates (|NWB| - |WB|), i.e. the difference in distances from the AP axis.

A linear regression model was used to analyze the mJSW difference and its association with the ML stability of the TKA. In this model the variables $d_{AP}$ and $d_{ML}$ were used as covariates. The rationale for using them is that the insert surface of the Triathlon total knee is not flat and therefore a difference in contact locations is also related to a difference in mJSW measured. This adds variability, which is not related to knee laxity, and therefore adding the variables $d_{AP}$ and $d_{ML}$ gives a better distinction between these effects.

4-3 Results

Table 4-6 shows the descriptive statistics of the WB and NWB mJSW values and their difference. On average, there was a positive difference over the 23 TKAs (0.28 mm medial and 0.20 mm lateral), meaning that a larger mJSW was measured in NWB position. The standard deviation of the mJSW difference was 0.54 mm medially and 0.47 mm laterally. The standard deviations of the WB and NWB mJSW values were larger than that of the mJSW difference, because the former include inter-patient variability of the inserted liner thickness, which can be either 8 mm, 10 mm or 12 mm for the Triathlon total knee.

Table 4-6. The means, standard deviations (SD) and ranges of the WB and NWB mJSW measurements and their difference (diff). All values are expressed in millimeters.

<table>
<thead>
<tr>
<th></th>
<th>WB</th>
<th>NWB</th>
<th>diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N = 23)</td>
<td>Mean</td>
<td>8,03</td>
<td>8,31</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1,77</td>
<td>1,80</td>
</tr>
<tr>
<td></td>
<td>[min-max]</td>
<td>[5.89 – 13.29]</td>
<td>[5.90 – 12.98]</td>
</tr>
<tr>
<td>Lateral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(N = 23)</td>
<td>Mean</td>
<td>8,40</td>
<td>8,60</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1,82</td>
<td>1,87</td>
</tr>
<tr>
<td></td>
<td>[min-max]</td>
<td>[6.05 – 13.03]</td>
<td>[6.12 – 13.80]</td>
</tr>
</tbody>
</table>
The distributions of the contact locations for the WB and NWB positions are displayed in Figure 4-11. For the medial condyle, the WB and NWB distributions are very similar, albeit the NWB distribution was 2.5 mm more anterior on average (t-test, \( p = 0.02 \)) and had a larger variation in the direction of the ML coordinate.

**Figure 4-11.** Scatterplots of the mJSW coordinates of the examinations for all TKAs and both WB and NWB datasets. (A) overview with the complete dataset and the perimeter of a size 4 triathlon tibia component as reference. On the right, zoomed in views of the medial (B) and lateral (C) datasets are shown. The ellipses indicate the 95% confidence interval of the data (1.96/\text{std dev} in the AP and ML directions).

**Table 4-7.** Summary of the linear regression model. Values and confidence intervals (95% CI) of the coefficients in the linear regression model. Values are expressed in mm mJSW difference per 1 unit change in the coefficient. The dependent variable is the difference in mJSW between NWB and WB positions. Coefficient values printed in bold are statistically significant (\( p < 0.05 \), Wald Chi Square)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Medial condyle</th>
<th>lateral condyle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Sig.</td>
</tr>
<tr>
<td>Intercept</td>
<td>.069 mm</td>
<td>0.16</td>
</tr>
<tr>
<td>( d_{ML} )</td>
<td>-.368 mm/mm</td>
<td>0.00</td>
</tr>
<tr>
<td>( d_{AP} )</td>
<td>-.040 mm/mm</td>
<td>0.01</td>
</tr>
<tr>
<td>ML_stab = 5-9deg</td>
<td>.362 mm</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table 4-7 shows the results of the regression analysis. The analysis showed that ML stability has a significant influence on the mJSW difference for the medial condyle. Four TKAs had a medium stability (5-9 deg) and 19 TKAs had a high ML stability (< 5 deg). On average, TKAs with a medium stability had a 0.362 mm larger mJSW difference ($p=0.01$) compared to TKAs with a high stability. This finding confirms the hypothesis that the difference in mJSW is related to knee laxity. No significant correlation or interactions were found between any of the coefficients $d_{ML}$, $d_{AP}$ and ML stability (Pearson’s correlation and $t$-tests).

A strong association was found between the mJSW difference and the difference in contact location ($d_{ML}$ and $d_{AP}$). The coefficient for $d_{ML}$ had the largest magnitude and has the following meaning: a 1 mm shift in contact location further from the center AP axis in the NWB position with respect to the WB position relates to a change in mJSW difference of -0.368 mm laterally and -0.265 mm medially.

To display the effect of ML stability, Figure 4-12 shows a scatterplot of the mJSW difference both for the original data (A) and the residual data (B) after the effects of the covariates $d_{ML}$ and $d_{AP}$ are corrected. As can be seen, in the residual data the variance is much lower and more consistent over the subgroups. In addition, the difference between the stability groups for the medial condyle is distinguishable.

\[ \begin{array}{cc}
\text{Figure 4-12. Comparison of the mJSW difference between ML stability groups (A, original mJSW differences; B, mJSW differences corrected for $d_{AP}$ and $d_{ML}$, based on the linear regression model).} \\
\end{array} \]

4-4 Discussion

We found that the mJSW measured in non-weight-bearing position was larger than the mJSW measured in weight-bearing position. The mean difference for the 23 TKAs was 0.28 mm and 0.20 mm for the medial and lateral condyle respectively. This difference can be caused by both knee laxity, but also by a difference in the measurement location between the WN and NWB positions.

The regression analysis showed that the knee stability was strongly associated with the mJSW difference for the medial condyle. TKAs with a medium stability had a 0.36 mm higher mJSW difference compared to TKAs with a high stability. This effect can be seen in the residual plot of the mJSW differences (Figure 4-11) and was statistically significant in the linear regression model (Wald’s Chi Square, \( p = 0.001 \)).

This finding supports our proposition that the mJSW measured in non-weight-bearing patient position is influenced by knee laxity and this limits the applicability of the measurement to assess wear progression in previous longitudinal RSA studies. As PE wear is related to TKA stability, more prostheses may become unstable during follow-up and cannot be measured, leading to an unacceptable selection bias. Nonetheless, during the initial stage of PE wear progression (as long as a TKA remains stable) the mJSW loss could still be detectable and the measurement can be used as an early predictor. Since data on the TKA stability is available in most RSA studies, this is a topic worth further investigation.

We only found a significant effect of ML stability for the medial condyle. This can be explained by the way prostheses are implanted and wear progression occurs. During knee replacement surgery ligament abnormalities are balanced to provide stability to the prosthesis. As wear of total knee prostheses is dominant at the medial condyle, due to the adduction moments at the knee during walking, a relative instability is expected to occur most frequently at this condyle.

A limitation of the study is that only four TKAs were included with medium stability, which adds constraints to the conclusions concerning the effect of ML stability. In that regard, it is interesting to notice that the effect sizes were different per condyle
(0.36 mm medially vs. 0.071 mm laterally). This difference can be coincidental, as the confidence intervals of the medial and lateral effect sizes overlap. It is also possible that this difference is related to the kinematics of the knee prosthesis, i.e. knee laxity due to ML stability could differ per condyle.

We assumed that the relation between the mJSW difference and the difference in contact location between the weight-bearing and non-weight-bearing positions was linear, in order to separate the effects of physical difference in insert thickness and joint separation. This assumption seems correct because of the strong associations that were found in the regression model and that no covariation or interactions were found between the variables. Still, if the joint separation size is also related to the contact location, then its effect size can be suppressed by the linear model and an exact model of the insert height profile should be used if a more accurate description is required of this effect.

In conclusion, the insert thickness measurement in non-weight-bearing positions is compromised if the TKA is unstable, and should not be used in those cases. As no significant difference in mJSW was found between WB and NWB positions in TKAs with high stability, the mJSW measurement may still reveal wear trends based on NWB data if cases are carefully selected. The relation between increasing wear, its effect on stability of the TKA and the effect on the accuracy of mJSW measurements should be studied further before they can be used for wear assessment with existing RSA studies.

REFERENCES


