## Supplementary data

Table 3. RSA migration analysis of mean absolute translation and rotation along and about each orthogonal axis (log-values are backtransformed in the original scale)

|  | All-polyethylene mean ( $95 \%$ CI) $(\mathrm{n}=29)$ | Metal-backed marker-based mean ( $95 \% \mathrm{CI}$ ) ( $\mathrm{n}=28$ ) | $\begin{aligned} & \text { Metal-backed } \\ & \text { model-based } \\ & \text { mean }(95 \% \text { CI) } \\ & (n=28) \end{aligned}$ |
| :---: | :---: | :---: | :---: |
| Translation along transverse axis (mm) |  |  |  |
| 3 months | 0.14 (0.09-0.20) | 0.21 (0.15-0.27) | 0.20 (0.15-0.27) |
| 1 year | 0.14 (0.09-0.20) | 0.21 (0.16-0.27) | 0.21 (0.16-0.27) |
| 2 years | 0.19 (0.14-0.25) | 0.26 (0.20-0.32) | 0.26 (0.20-0.32) |
| Translation along longitudinal axis (mm) |  |  |  |
| 3 months | 0.12 (0.08-0.15) | 0.11 (0.08-0.15) | 0.12 (0.08-0.15) |
| 1 year | 0.13 (0.09-0.16) | 0.13 (0.09-0.16) | 0.15 (0.12-0.19) |
| 2 years | 0.10 (0.07-0.14) | 0.15 (0.11-0.18) | 0.17 (0.14-0.21) |
| Translation along sagittal axis (mm) |  |  |  |
| 3 months | 0.19 (0.11-0.27) | 0.22 (0.14-0.31) | 0.24 (0.16-0.33) |
| 1 year | 0.24 (0.16-0.33) | 0.38 (0.29-0.47) | 0.38 (0.29-0.48) |
| 2 years | 0.25 (0.17-0.34) | 0.44 (0.35-0.55) | 0.43 (0.34-0.53) |
| Rotation about transverse axis ( ${ }^{\circ}$ ) |  |  |  |
| 3 months | 0.38 (0.27-0.49) | 0.23 (0.14-0.34) | 0.25 (0.15-0.35) |
| 1 year | 0.48 (0.37-0.61) | 0.38 (0.27-0.49) | 0.40 (0.30-0.52) |
| 2 years | 0.47 (0.36-0.59) | 0.47 (0.35-0.59) | 0.45 (0.33-0.57) |
| Rotation about longitudinal axis (degrees) |  |  |  |
| 3 months | 0.18 (0.11-0.25) | 0.19 (0.13-0.27) | 0.29 (0.22-0.38) |
| 1 year | 0.20 (0.13-0.28) | 0.24 (0.17-0.31) | 0.38 (0.30-0.47) |
| 2 years | 0.20 (0.13-0.27) | 0.28 (0.20-0.35) | 0.41 (0.32-0.50) |
| Rotation about sagittal axis ( ${ }^{\circ}$ ) |  |  |  |
| 3 months | 0.26 (0.18-0.33) | 0.24 (0.16-0.32) | 0.21 (0.14-0.28) |
| 1 year | 0.32 (0.25-0.40) | 0.28 (0.20-0.36) | 0.24 (0.16-0.31) |
| 2 years | 0.34 (0.26-0.42) | 0.33 (0.25-0.41) | 0.25 (0.18-0.33) |

## Appendix

## Prosthesis migration

RSA is generally used to calculate prosthesis migration, defined as the change in position and orientation of a prosthesis with respect to the bone (Valstar et al. 2005, ISO 16087:2013(E) 2013). Tantalum markers inserted into the bone and added to the prosthesis define landmarks that are used for accurate calculations. In Model-based RSA, the prosthesis itself is used as a marker, making prosthesis markers obsolete. By matching the virtual projections of a 3D surface model of the prosthesis with the detected roentgen projections of the prosthesis, the position and orientation of the prosthesis is calculated (Kaptein et al. 2003). First step in migration calculation is the landmark transform that aligns the bone markers in the follow-up moment ( t 1 ) with the bone markers in the reference moment ( t 0 ) (Valstar et al. 2005). This removes the "patient movement" between the different RSA acquisition moments (Figure A1).

Table 4. Adjusted RSA migration analysis of log-transformed maximum total point motion (logMTPM)

|  | Mean difference in logMTP Marker-based ${ }^{\text {a }}$ | tween groups (95\% CI) Model-based ${ }^{\text {b }}$ |
| :---: | :---: | :---: |
| Treatment effect (reference: all-polyethylene) |  |  |
| 3 months | -0.007 (-0.049 to 0.036) | 0.013 (-0.031 to 0.057) |
| 1 year | 0.014 (-0.029 to 0.057) | 0.025 (-0.019 to 0.069) |
| 2 years | 0.030 (-0.013 to 0.074) | 0.038 (-0.007 to 0.083) |
| Sex effect (reference: male) |  |  |
| 3 months | 0.008 (-0.043 to 0.045) | 0.002 (-0.044 to 0.047) |
| 1 year | 0.017 (-0.027 to 0.062) | 0.011 (-0.034 to 0.057) |
| 2 years | 0.026 (-0.020 to 0.068) | 0.031 (-0.015 to 0.077) |
| Surgeon effect (reference: surgeon 1) |  |  |
| 3 months | 0.083 (0.040 to 0.126) | 0.077 (0.033 to 0.121) |
| 1 year | 0.113 (0.071 to 0.156) | 0.099 (0.055 to 0.143) |
| 2 years | 0.132 (0.089 to 0.174) | 0.114 (0.070 to 0.158) |
| ${ }^{\text {a }}$ All-polyethylene $(\mathrm{n}=29)$ versus marker-based metal-backed $(\mathrm{n}=28)$, <br> ${ }^{\text {b }}$ All-polyethylene $(\mathrm{n}=29)$ versus model-based metal-backed ( $\mathrm{n}=28$ ). |  |  |



Figure A1. Transformation of the follow-up bone markers in the followup moment ( t 1 ) to the bone markers in the reference moment ( t 0 ) is performed (note that, in this example, the prosthesis migration is exaggerated)

The second step is the calculation of the change in position and orientation of the prosthesis between the reference moment and the follow-up moment. This change in position and orientation is thus relative to the bone markers.


Figure A2. The left side of the figure shows the position of the reference origin of the 3D surface model (Model Origin) used for model-based RSA migration calculation and the right side of the figure shows the reference origin in the geometric center of the polyethylene markers (Markers Origin) used for marker-based RSA migration calculation. The X -axis is the transverse axis, the Y -axis is the longitudinal axis, and the Z -axis is the sagittal axis.

Figure A3. The prosthesis model migrated from to (blue) to t1 (red). The orange vector indicates the translation of the Model Origin in Model-based RSA. For the Markers Origin, translation is different (green vector).

tion differs slightly due to the difference of the reference origins: the upper row is for the Models Origin reference and the lower row is for the Markers Origin reference.

## Point motion, maximum total point motion

For individual points on the prosthesis (e.g., markers attached to the prosthesis, virtual markers or 3D surface model points) the translation along each axis can be calculated from the x -, $y-$, and $z$-coordinates of these points at $t 1$ and $t 0$. The point motion can be calculated based on Pythagoras' theorem:
point motion $=\sqrt{ }\left(\mathrm{Tx}^{2}+\mathrm{Ty}^{2}+\mathrm{Tz}^{2}\right)$
In Figure A5 the point motion of 4 virtual markers on the tibia prosthesis is shown.

The point motion of the virtual markers from Figure A5 is:

|  | x | y | z | Point motion (mm) |
| :--- | :---: | :---: | :---: | :---: |
| Front | 10.41 | 19.89 | 0 | 22.45 |
| Lateral | 15.56 | 39.12 | 0 | 42.10 |
| Medial | 5.26 | 0.67 | 0 | 5.30 |
| Tip | -6.15 | 24.33 | 0 | 25.09 |

The virtual marker with the largest point motion is the "Lateral" marker. The virtual marker with the smallest point motion is the "Medial" marker. In the example migration shown in this Appendix, the tibia model rotates approximately around the medial edge of the prosthesis. Virtual markers close to this "true" rotation point have small point motions, and virtual markers at larger distances from this true rotation point have larger point motions. Maximum total point motion (MTPM), which is frequently used to summarize the migration of a prosthesis, is the length of the translation vector of the marker or virtual marker in a rigid body that has the greatest migration. For model-based RSA, MTPM is the length of the translation vector of the point on the model that moved the most.
The difference between the x -, y -, and z -coordinates at t 0 and tl used to calculate point motion is independent of the selected reference origin. As a consequence, point motion, including MTPM, will not differ between migration calculations with different reference origins.


Figure A4. The upper row illustrates RSA migration of the tibia prosthesis from t0 (blue) to t1 (red) using the Model Origin: the model is rotated about the Z -axis $\left(-30^{\circ}\right)$, and translated along the X -axis ( 10 mm ) and Y -axis ( 20 mm ). The lower row illustrates RSA migration of the tibia prosthesis from t0 (blue) to t1 (red) using the Markers Origin: the model is rotated about the Z -axis $\left(-30^{\circ}\right)$, and translated along the X -axis $(16.5 \mathrm{~mm})$ and Y -axis ( 18.25 mm ).


Figure A5. The change in position of 4 virtual markers on the tibia prosthesis model from to (blue) to t1 (red)

## In summary

- The position of the reference coordinate system, used to describe prosthesis migration, has an effect on the calculated prosthesis translations but not on the prosthesis rotations.
- The translation of individual markers, virtual markers, or points on the 3D surface model are not affected by the position of the reference origin. Hence, MTPM is not affected by changing the reference origin.
- In general it can be stated that the further away from the true point of rotation a (virtual) marker lies, the larger the calculated translations are. This also applies to the reference origin, as this is also a "point."
- Changing the orientation of the reference coordinate system (not demonstrated in this Appendix) does have an effect on the calculated translations and rotations of the prosthesis.
- Changing the orientation of the reference coordinate system does not affect the magnitude of individual point motion, but it does affect the direction of the point motion.


## Appendix references

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