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Implementation and validation of an implant-based coordinate system for RSA migration calculation

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ABSTRACT

An *in vitro* radiostereometric analysis (RSA) phantom study of a total knee replacement was carried out to evaluate the effect of implementing two new modifications to the conventional RSA procedure: (i) adding a landmark of the tibial component as an implant marker and (ii) defining an implant-based coordinate system constructed from implant landmarks for the calculation of migration results. The motivation for these two modifications were (i) to improve the representation of the implant by the markers by including the stem tip marker which increases the marker distribution (ii) to recover clinical RSA study cases with insufficient numbers of markers visible in the implant polyethylene and (iii) to eliminate errors in migration calculations due to misalignment of the anatomical axes with the RSA global coordinate system. The translational and rotational phantom studies showed no loss of accuracy with the two new measurement methods. The RSA system employing these methods has a precision of better than 0.05 mm for translations and 0.03° for rotations, and an accuracy of 0.05 mm for translations and 0.15° for rotations. These results indicate that the new methods to improve the interpretability, relevance, and standardization of the results do not compromise precision and accuracy, and are suitable for application to clinical data.

1. Introduction

The technical developments of radiostereometric analysis (RSA) (Selvik, 1989) continue to expand its capability as a research tool for describing the micromotion of orthopaedic implants *in vivo*. This highly accurate technique uses at least three tantalum markers inserted in both the implant and the host bone to define these rigid bodies. Stereo radiographs taken with a calibration box enable the calculation of three-dimensional movement of the implant relative to the bone. Micromotion can be measured as permanent migration of the implant over time or inducible displacement of the implant, an elastic deformation in response to an applied load (Selvik, 1989; Ryd, 1992).

One limitation of representing the implant with inserted markers for RSA micromotion calculation is that results are described as translations and rotations relative to a global coordinate system defined by the RSA calibration box. If the joint under examination is not aligned with the calibration box, the micromotion results will not correlate with the anatomical axes and will be inconsistent between subjects. Using implant landmarks to define an implant-based coordinate system for the calculation of RSA migrations may provide results that will be more clinically relevant since the measurement and anatomical axes are aligned.

Another issue that arises in radiostereometric analysis of total knee replacements (TKR) is that due to the narrow joint space in a total knee replacement, the markers in the tibial component polyethylene are often obscured by the metal implant components. This leads to different markers being visible in different exams, changing the location of the centroid of the markers which can lead to inconsistencies. In addition, since a minimum of three markers is required to define a rigid body, clinical cases may be lost when only two implant markers are visible. The identification of a reliable landmark of the metal tibial component can serve as an additional implant marker in all exams to provide improved marker distribution which encompasses the whole implant, not just the tibial plateau, and also recover otherwise unusable RSA cases.

A similar approach has been used successfully in RSA studies of the hip (Kiss et al., 1995; Kaptein et al., 2006) where easily identifiable features of the femoral component were used to create a geometric model of the implant, but to date, this approach has not been used for TKR.

Evaluations of new RSA techniques are commonly performed with phantom studies which assess the precision and accuracy of RSA systems and analysis methods (Valstar et al., 2000; Kaptein et al., 2006; Madanat et al., 2005). The objective of this study was

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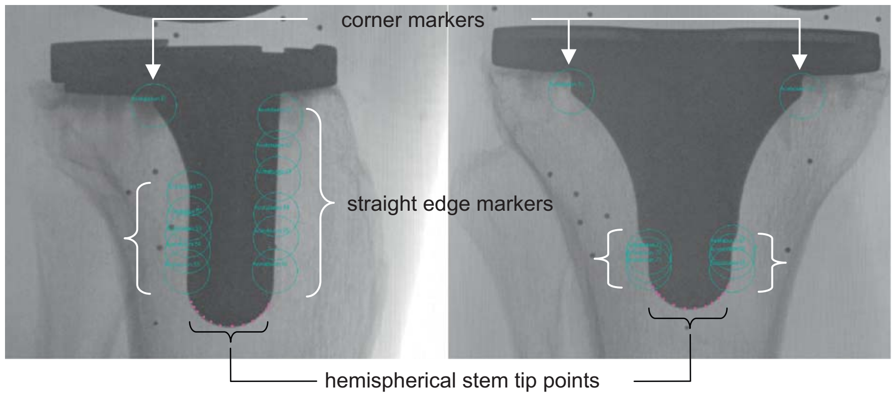

Fig. 1. Landmarks of the implant used to define the implant-based coordinate system identified on the stereo x-rays in the RSA software. Corners are identified by adding markers; the software matches the correct corner marker in the anterior–posterior view with the visible corner marker in the medial–lateral view. The straight edges are identified by placing a series of markers along the edges. The stem tip centre requires the user to add points along the periphery, which are used by the software to calculate the centre of a sphere.

to use an RSA migration phantom study to evaluate the effect of two modifications to the conventional RSA procedure intended to improve standardization of analysis and interpretation of results: (i) adding the centre of the hemispherical tip of the tibial component stem as an implant marker and (ii) using implant landmarks visible in the stereo X-rays to define an implant-based coordinate system for the calculation of migration results.

2. Methods

2.1. Radiostereometric analysis

A biplanar RSA set-up (Valstar et al., 2002) was used with two X-ray tubes (one fixed X-ray head: Model Ultranet-SA, GE Medical Systems, Monza, Italy; one portable X-ray head: Model 46-194759G1, General Electric Company, Milwaukee, WI, USA) oriented at 90° to each other and a biplanar calibration box (Tilly Medical Products AB, Lund, Sweden). X-rays were scanned from AFGA-Gevaert NV CRMD4.0 cassettes (35×43 cm) (Mortsel, Belgium) with an AGFA-Gevaert NV CR85-X digitizer, producing images with a spatial resolution of 6 pixels/mm and a greyscale resolution of 12 bits/pixel. Radiostereometric analysis was performed using commercial software (RSA-CMS, Version 4.3, MEDIS medical imaging systems BV, Leiden, The Netherlands).

2.2. Implant

The ADVANCE tibial component (Wright Medical Technologies, Inc., Arlington, TN) was used since the techniques developed in this study were to be applied to a clinical RSA study of this implant.

2.3. Addition of an implant landmark as a marker

The tip of the tibial component stem was selected as the landmark to be used as an additional implant marker. Specifically, the centre of the hemispherical tip of the tibial component stem was found by using the circle-finding feature of the RSA-CMS software. This function is intended for identifying the spherical femoral head of a hip replacement (Karrholm et al., 1997). The operator was required to place a series of points along the circular contour of the stem tip in both stereo X-rays which were used by the software to calculate the centre of a sphere. The centre point was then used as an implant marker. The allowable crossing line error of the centre point was set to 0.1 mm, the same limit was applied to the tantalum markers.

2.4. Definition of the implant-based coordinate system

Landmarks of the tibial component were used to define a coordinate system that was aligned with the implant, regardless of the orientation of the leg relative to the calibration box. Landmarks were selected that were reliably visible in the X-rays and which provided the necessary geometries to create an orthogonal coordinate system. These landmarks were identified in the commercial RSA software by manually placing software markers at these points. The landmarks used were (i) the centre of the stem tip as described in the previous section, (ii) the longitudinal axis of the stem defined by the straight edges in the X-rays, and (iii) the corners of the fins on the tibial component (Fig. 1). To determine the longitudinal axis of the stem, best-fit lines were generated through the points on the straight edges and the longitudinal axis of the stem was found by averaging the four visible straight edges, similar to methods used by Kiss et al. (1995) and Kaptein et al. (2006). A single fin corner was detected using the commercial RSA software to match the single point in the medial–lateral image with the correct point in the anterior–posterior image, providing the 3D location of this landmark. Crossing line errors for the corner were limited to 0.1 mm. The second corner was geometrically determined by finding the intersection of the projection line to the second corner point in the anterior–posterior view with the plane perpendicular to the longitudinal axis already determined, containing the first corner. The implant-based coordinate system was defined such that the y-axis was aligned with the longitudinal axis of the implant stem and the x-axis passed through the corners of the two fins (Fig. 2A). To ensure orthogonality of the coordinate system, the axis through the corners was used as a first estimate of the x-axis, the z-axis was calculated as a cross product of the y- and x-axis, and the true x-axis was recalculated as the cross product of the y- and z-axis. The origin of the coordinate system was placed at the centre of the hemispherical tip of the stem.

2.5. Migration calculations

Custom Matlab (The Mathworks, Inc., Natwick, MA) software was used to define the implant-based coordinate system based on these landmarks and to recalculate the migration results in this new coordinate system. For the custom software, the least squares optimization method as described by Challis (1995) was used to calculate transformations incorporating all marker information. All rotations and translations were calculated for a right-hand coordinate system with the signs later corrected to comply with the conventions proposed by Valstar et al. (2005) such that the x-axis points medially, the y-axis proximally, and the z-axis anteriorly.

Migration parameters calculated by the RSA system include translations and rotations of the implant about the x-, y-, and z-axis, and the maximum total point motion (MTPM) which is the length of the 3D vector of the implant marker which moved the most (Ryd et al., 1995).

To compare the effects of the two modifications to the RSA procedure, three measurement methods were used to calculate the migration parameters: (i) conventional RSA as calculated by RSA-CMS about the global coordinate system of the calibration box (*global*), (ii) conventional RSA including the stem tip centre as an implant marker (*global+stem*), and (iii) a local implant-based coordinate system defined by implant landmarks including the stem tip centre as an implant marker (*local+stem*).

2.6. Phantom study validation

Separate translational and rotational phantom studies were carried out to validate the implant-based coordinate system method and to quantify the system precision and accuracy. The phantom model for both studies was assembled to permit known movements of the implant with respect to a replica tibia. These known translations and rotations were the expected migration output of RSA-CMS.

The phantom model consisted of an ADVANCE tibial component and polyethylene insert mounted on a set of micrometers, and a fixed tibial replica bone (Sawbones, Pacific Research Laboratories, Inc., Vashon, WA) within the biplanar calibration box. Tantalum RSA marker beads (0.8 mm in diameter;