TITLE: A Comparison Between Convergent and Bi-Plane X-Ray Photogrammetry Systems Used to Detect Total Joint Loosening

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Arthritic patients severely crippled and in extreme pain can be made to walk again without ambulatory aids, pain free with successful total joint replacement. The number one complication of total knee replacement is loosening which has been reported to be as high as 25% in long term follow-up. The early symptom of component loosening is pain on initial weight bearing. Later, x-ray lucency develops at the bone-component interface followed by migration and possible component dislocation. If allowed to progress to the final stage, bone loss results and reconstruction is extremely difficult. Loose prosthetic components should be identified early when an elective revision can be made.

X-ray photogrammetry is an accurate method of measuring total joint loosening and migration. Two systems for accomplishing these measurements have been developed in the United States. One method uses bi-plane geometry and the other, convergent geometry. Both systems are being used currently to measure implant loosening. The purpose of this paper is to compare each systems' strengths and weaknesses as a clinical tool and the accuracy by comparing calibrated and measured motions on a model.

Criteria of Clinical Acceptability:
The following criteria are important for a clinically useable system:
1. Accuracy and resolution better than 0.5 mm.
2. Permits the patient to be measured in a variety of positions both with the effected extremity loaded and unloaded.
3. A data processing system which gives results in one day.
4. Minimal x-ray exposure to the patient.

System Geometry:
If an object point is imaged on two radiographs, the spatial position of that point can be determined provided two criteria are met. First, the orientation of the two films (radiographs) must be known in terms of a common coordinate system and the projected object points on each of the films must be determinable in terms of this common coordinate system. Second, the location of the two point sources (x-rays anode perspective centres) must also be known in terms of this same coordinate system. (R) (Brown, et.al., 1976).

In satisfying the above mentioned criteria, the Cleveland system incorporates a rectangular reference frame, hence the "biplane" designation. A simplified plan view of this configuration is illustrated in Fig. 1-a. The reference frame supports two film cassettes at right angles, and nearly coplanar with each film is a reference plane containing calibration wires. Parallel to the film and reference plane are calibration plate planes which contain markers. The principle axes of the two x-ray anodes are orthogonal. Reference markers for each film plane consist of a set of orthogonal wires which are imaged at each exposure. These two sets of wires define the common three-dimensional coordinate system of the frame and they have been precisely aligned and positioned along with the calibration markers during the frame's construction. The role of the calibration markers is to provide control for the multi-line spatial intersections which determine the common system coordinates of the two anode perspective centres.

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Whereas the Cleveland system employs a biplane technique, the geometry of
the Seattle system comprises a convergent imaging configuration, incorpora-
ting a single film plane. This geometry is illustrated in Fig. 1-b. Of the
two parallel planes shown in the figure, one is a reseau plate behind which
the film cassette is mounted, while the second is a plexiglass plate on
which 45 calibration markers are engraved. In the construction of the
Seattle system reference frame, less attention was paid to precise relative
positioning and alignment of the two planes, because the common three-
dimensional coordinate system for the frame was established photogrammetri-
cally after construction.   (see Fraser & Abdullah, 1980).

During the imaging process, following the anode "resection" phase, the
calibration plate of the Seattle frame is removed and the patient or object
being imaged is positioned in front of the reseau plate (effectively, the
film plane). With the Cleveland system, the patient is located within the
rectangular frame and the calibration plates remain in place throughout
the survey. Using the latter system, there is a saving of two exposures;
these exposures being required in the Seattle system for the initial anode
perspective centre calibration.

In terms of attainable precision, the overall geometric strength of the bi-
plane configuration in the determination of the spatial position of object
points is viewed as being more desirable than the 40° convergent configura-
tion employed in the Seattle system. However, at the present time the re-
quired point coordinate accuracy for orthopaedic application is approximately
0.3 to 0.5 mm. and in this context both geometric arrangements appear to be
equally favorable. The clinical applicability of each of the system
geometrics is discussed in a following section.

Data Acquisition and Computations:
Typically, the initial phase of the data acquisition for an x-ray photo-
grammetric system is directly analogous to that of traditional analytical
photogrammetric surveys: The x-y coordinate observations of image points
on the film (radiographs). Both the Cleveland and Seattle techniques
incorporate a computerized data acquisition system. In Cleveland, an x-y
encoding light table was especially constructed for use in the bi-plane
radiography research (see Brown, et.al.,1976), whereas in Seattle, an Altec
digitizer is used for the image coordinate observations. Both instruments
have a repeatability and accuracy of around a few tens of micrometers.
     For the initial transformation of the observed image coordinates
into the reference frame coordinate system, two very different approaches
have been adopted. In the Cleveland system, reference axes are aligned by
eye on the encoding light table and the origin of the reference coordinate
system is visually set. With the adoption of such a procedure, there are
essentially no degrees of freedom afforded in the image coordinate to
reference coordinate mapping. Thus, there is the inherent assumption that
both film deformation and distortion, and systematic x-y encoding errors
are consistent and self-correcting.

As has been mentioned, the Seattle system incorporates an accurately
calibrated reseau plate and it is, therefore, possible to compensate for
some of the more familiar components of film deformation and distortion in
the initial image coordinate transformation. For example, if a linearized
form of the standard projective equation is used for the mapping, there is
a compensation of any first-order affinity within the image x-y coordinate
system (typically due to longitudinal stretching). In addition, there is
a partial compensation of second-order image distortion and non-parallelism

between the film housed in a cassette and the reseau plate.

Following the initial image to reference frame coordinate transformation, the computational phases of each system follow essentially the same steps. First, the common reference system coordinates of the anode perspective centres are determined and this is followed by the calculation of the coordinates of all object points via space intersections. Aspects of these computations are discussed with the mathematical model descriptions presented in a following section. Subsequent computations include the calculation of point to point distances which are used in the evaluation of relative prosthetic implant motion, and the determination of selected statistical information.

For the computational phase the Cleveland system employs an in-house Nova computer, whereas at the present time the Seattle system uses a separate coordinatograph and BDP 11/34 Data Acquisition.

Mathematical Models:

The mathematical models and computational algorithms adopted for the two independently developed x-ray photogrammetric techniques have been described by Brown, et.al. (1976), for the Cleveland system and Fraser & Abdullah (1980), for the Seattle system. The fundamental formula of each model is the equation of a ray, R, passing through the image space, defined by the spatial positions of two points p' (x', y', z') and p", (x", y", z") which lie along that ray. The coordinates of any third point p (x, y, z), which is collinear with p' and p", then satisfy the following two equations which are linear in terms of the unknowns x, y and z:

$$\begin{bmatrix} m & -1 & 0 \\ n & 0 & -1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} - \begin{bmatrix} mX'-1Y' \\ nX'-1Z' \end{bmatrix} = 0$$

Here, 1, m and n are the direction cosines. If two or more rays pass through a point to be determined, p, then a solution for x, y and z can be effected by solving the resulting overdetermined linear system.

The approach adopted by Brown, et.al.,(1976) is to take the midpoint of the vector N_{12}, mutually perpendicular to any pair of "intersecting" rays R_1 and R_2, as the location of the object point p (x, y, z). In both systems the number of rays R_i available for the anode resection phase, or perspective centre determination, is typically well in excess of two. In such cases, under the Cleveland system, ray pairs R_i R_j are considered only one at a time, thus yielding a number of solutions (x, y, z)$_{ij}$ for the coordinates of point p. The final coordinates are then obtained by taking the mean value of all determinations (x, y, z)$_{ij}$. This somewhat non-rigorous approach does allow a measure of error evaluation to be carried out with regard to gross error detection. However, the error value E, which is defined by Brown, et.al. (1976), as being one-half the magnitude of the vector N_{ij}, is of limited application for ascertaining the precision of the derived three-dimensional coordinates of any object point p, or for quantifying the precision of any measure of resulting prosthesis loosening which is determined. Motion in excess of two standard deviations of the

system's tested accuracy is considered significant.

A variation of the mathematical model employed in the spatial intersection method of steroplotter perspective centre calibration has been employed in the Seattle system. The particular formulation, detailed by Fraser and Abdullah (1980), represents a more rigorous treatment in that Egs (1) are first linearized with respect to the coordinates (x', y', z') and (x", y", z"), which are in turn treated as observed quantities of known priori precision. The resulting condition equations with parameters x, y and z are then solved according to the method of least squares. Thus, the parameters and observations of the linear model lend themselves to statistical assessment. Two important measures of precision that are determined are the posteriori variance-covariance matrix for the coordinates of any object point p (x, y, z) and the variance of the calculated distances between landmarks on the prosthesis and those in the bone or polymethylmethacralate. From the latter quantity it is possible to ascertain whether significant implant motion has occurred, given a particular confidence level.

In order to compare the accuracy of the two photogrammetry systems, a plexiglass model was used. This consisted of a base cylinder and a rotating cap containing steel markers Figure 3. Markers 1-4 in the cylinder provided the basis for a reference coordinate system from which the coordinates of markers 5-7 in the rotating cap could be computed.

The cap could be rotated into 11 calibrated positions. Small or large rotations were produced by appropriate matching of cap and cylinder slots. Fixation during measurement was achieved by a locking pin passed through the corresponding slots. Motion was determined using the computed coordinates of the reference and selected positions. These same motions were then measured using x-ray photogrammetry and compared to the computed values Table 1.

Clinical Applicability:
With the biplane radiographic technique, simultaneous exposures of standard A-P and lateral views are made, thus providing the routinely obtained clinical radiographs. On the other hand, with the convergent configuration employed in the Seattle system, extra x-ray exposures will be required if A-P and lateral projections are sought for clinical application. Taking into account the increasing concern over acceptable patient radiation dosage levels, the Cleveland system displays the advantage of typically requiring the exposure of fewer radiographs for routine patient studies.

However, the advantages gained in terms of minimizing radiation dosage by utilizing one pair of biplane radiographs for clinical and non-clinical (photogrammetric) purposes is partially offset by the difficulty of observing a given marker in both planes.

In the case where landmarks are located within the polymethylmethracylate between the implant and the bone, there is a very limited allowable tolerance in orienting the patient such that a sufficient number of landmarks will appear in the A-P and lateral views. As can be seen from the simplified diagram, Fig.2, the convergent configuration affords more leeway in patient orientation. This often results in fewer trial exposures being required before a satisfactory landmark coverage is achieved. Yet, the Cleveland system offers a more flexible patient alignment with respect to the x-ray principle axes.

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From the clinical criteria and accuracy comparisons it appears that both systems meet the requirements for measurement of total joint loosening. Assuming both techniques have on-line, in-house computer accessability the time to obtain results is directly related to measurement of the x-rays. The Seattle system requires more points to be measured but if many patients are measured in a group, only one calibration needs to be done. With the Cleveland system, calibrations are done for each patient but there are fewer points used. Thus, with only one patient per day or per week, the Cleveland system would take less measurement time, but if large numbers of patients were going to be done, the Seattle system might be less time consuming.

The Seattle system was designed for maximum flexibility where the convergent angles can vary up to 45°. Thus, it can be used for a variety of anatomical areas including knees, hips, ankles and even patellar motion, some of which require convergent angles less than 45°. Therefore, if the system is intended to study just hips or knees, the Cleveland system is simpler and probably preferable. If one requires a maximum degree of flexibility for a wide variety of anatomical studies, then the Seattle system may be preferable.

What is the best system? The answer is that each institution should study its own requirements and identify what population will be studied, the available expertise, computer facilities and x-ray equipment and then decide which of the two systems presented in this paper best fits their needs.

References:

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2. Fraser, C.S. and Abdullah, Q.A. (1980): A Simplified Mathematical Model for Applications of Analytical X-Ray Photogrammetry in Orthopaedics. Presented paper Comm. V., 14th International Congress of the ISP, Hamburg, Germany, July, 1980.
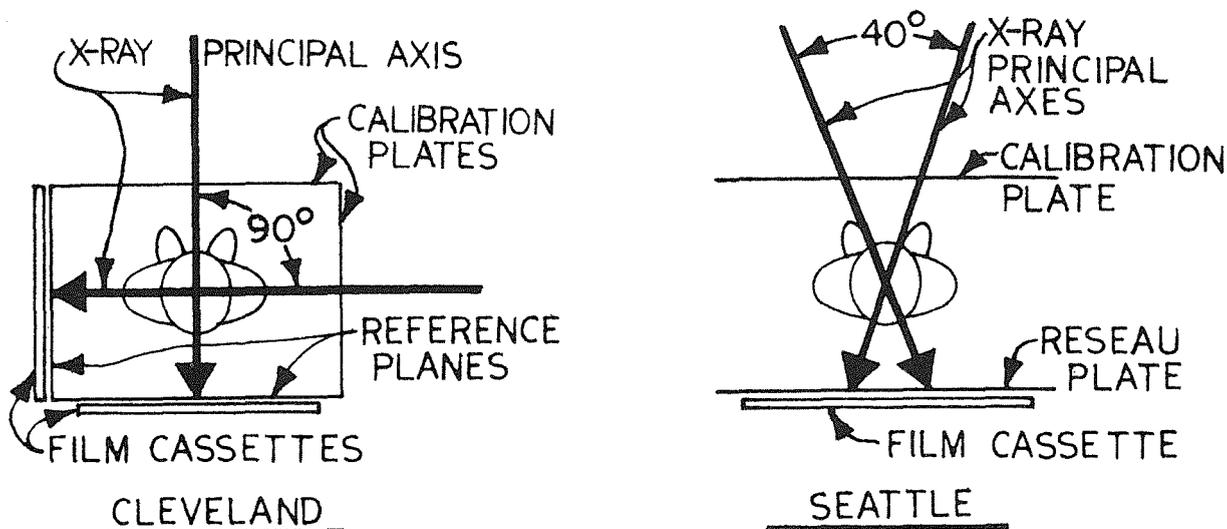
FIG. I: SYSTEM GEOMETRIES
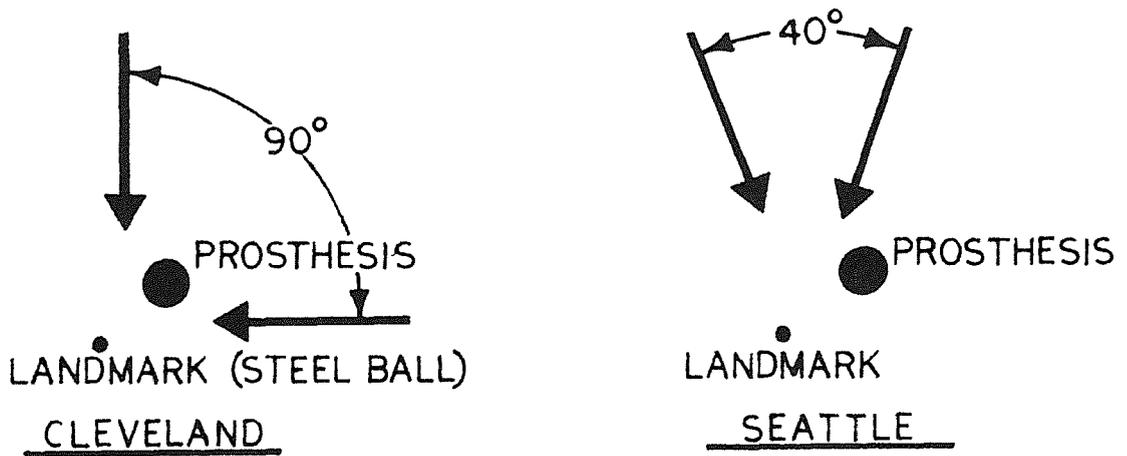
FIG.2: LANDMARK COVERAGE TOLERANCE

CAP

4"

1-3/4"
BASE
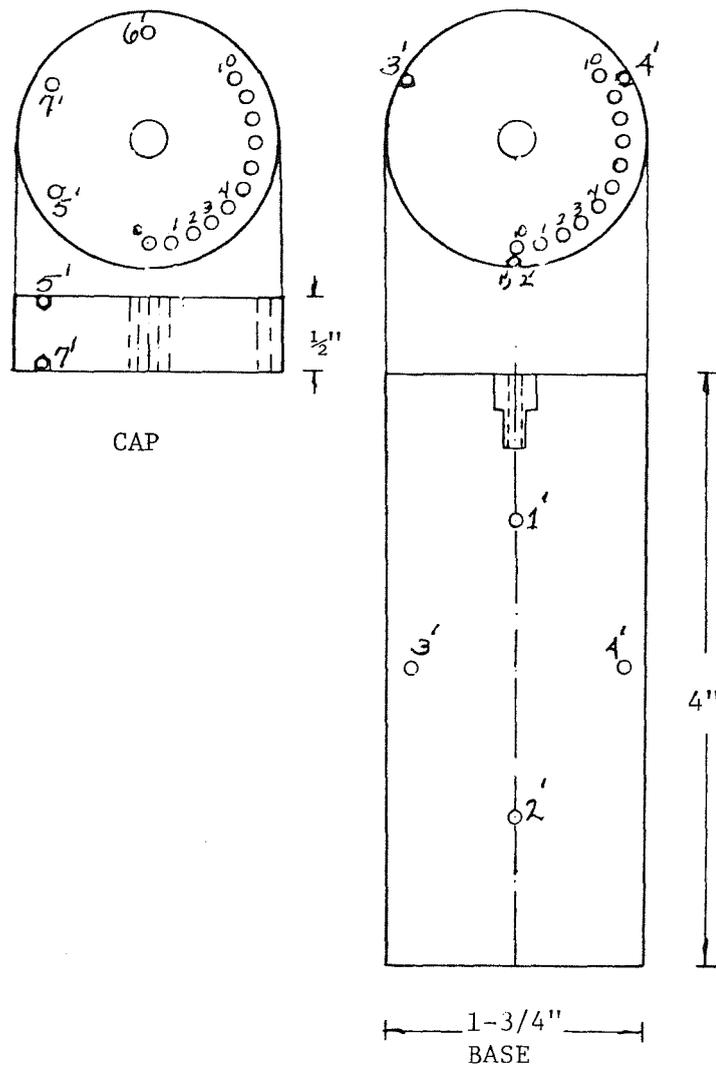
Figure 3. Plastic model used to compare Seattle and Cleveland
           Photogrammetry Systems.

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Model Setting	Calibrated Distance	Ball #5 Seattle		Ball #5 Cleveland	
		Motion	Residual	Motion	Residual
0-4	.338	.282	-.056	.385	+.047
0-8	.677	.669	-.008	.728	+.051
1-0	3.967	4.055	+.088	3.899	-.068
1-2	4.138	4.083	-.055	4.192	+.054
1-4	4.306	4.207	-.099	4.134	-.172
2-0	7.893	Marker not Visible		7.932	.039
2 x RSME			.154		.186

Model Setting	Calibrated Distance	Ball #6 Seattle		Ball #6 Cleveland	
		Motion	Residual	Motion	Residual
0-4	.338	Marker not Visible		.477	+.139
0-8	.677	.477	.200	.572	-.105
1-0	3.967	4.017	+.050	3.892	-.075
1-2	4.138	Marker not Visible		3.966	-.142
1-4	4.306	4.430	+.124	4.336	+.030
2-0	7.893	Marker not Visible		7.870	-.023
2 x RSME			.340		.214

Model Setting	Calibrated Distance	Ball #7 Seattle		Ball #7 Cleveland	
		Motion	Residual	Motion	Residual
0-4	.338	.472	+.134	.522	+.184
0-8	.677	Marker not Visible		.839	+.162
1-0	3.967	Marker not Visible		3.995	+.026
1-2	4.138	4.080	-.058	4.217	+.079
1-4	4.306	4.510	+.204	4.329	+.026
2-0	7.893	Marker not Visible		7.855	-.038
2 x RSME			.354		.235

Table 1

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