Accuracy of Measurement of Polyethylene Wear with Use of Radiographs of Total Hip Replacements

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Background: Although a number of methods are used to estimate polyethylene liner wear from radiographs of total hip replacements, there is no consensus with regard to the accuracy of these methods. The purpose of this study was to compare the accuracy of several such measurement methods with use of both laboratory radiographs and routine clinical radiographs.

Methods: A phantom apparatus was designed to simulate random values of three-dimensional wear, with varying degrees of cup abduction and anteversion, and to obtain anteroposterior and cross-table lateral radiographs with each value. Wear was measured with use of the Charnley duoradiographic method, the Livermore method, and the method described by Dorr and Wan, as well as with use of PolyWare and Hip32 software packages, both with and without three-dimensional measurements. Clinical wear was measured from conventional radiographs made prior to revision surgery in fourteen patients and was compared with wear measured directly from the retrieved liners with use of a coordinate measuring machine.

Results: With laboratory radiographs, median errors were 0.1 mm with the Livermore method and both computerized methods, 0.23 mm with the Charnley method, and 1.7 mm with the method of Dorr and Wan. Maximum errors were between 0.6 mm (Livermore) and 4.3 mm (Dorr and Wan). In contrast, with use of clinical radiographs, median errors ranged between 0.2 mm (Hip32) and 0.6 mm (Dorr and Wan). Maximum errors ranged between 1.8 mm (Dorr and Wan) and 2.5 mm (Livermore).

Conclusions and Clinical Relevance: With laboratory radiographs, computerized methods of polyethylene wear measurement offered distinctly greater accuracy than did manual methods; however, with clinical radiographs, they offered only slightly better accuracy. Although the increased accuracy of computerized methods may be necessary in research settings, manual methods provided sufficient accuracy for routine clinical assessment of wear.

Although a number of methods quantify polyethylene liner wear from radiographs of total hip replacements, no consensus has been reached with regard to the accuracy of these methods. The first attempt to measure polyethylene wear was the uniradiographic method described by Charnley and Cupic[1], modified later to be the duoradiographic method[2]. These techniques were developed for cemented polyethylene cups. Later, Livermore et al.[3] described a method that used a transparent overlay with concentric circles, similar to those used by Scheier and Sandel[4] and Buchhorn et al.[5], taking advantage of the margin of the femoral ball that is not obscured by the metal cup. In 1995, Dorr and Wan[6] described another method that measured wear only in one direction, in the face of the cup.

The first computer-based methods that we are aware of for quantifying wear were Maxima[7] (Centre for Hip Surgery, Wrightington Hospital, Wigan, Lancashire, United Kingdom) and EBRA[8] (Einzel-Bild-Roentgen-Analyse; Department of Orthopedics and the Institute for Mathematics and Geometry at the University of Innsbruck, Innsbruck, Austria). Shortly thereafter, Devane et al.[9,10] introduced PolyWare (Draftware Developers, Vevay, Indiana), which used points manually digitized on a tablet[9,10]. PolyWare was later modified to use computerized edge-detection subroutines[11]. Similarly, two other computerized methods, one described by Shaver et al.[12] and the other described by Martell and Berdia[13] (Hip32; University of Chicago Medical Center, Chicago, Illinois), used edge-detection-based software and interactive user interfaces[13].

To date, the accuracy of computer-based methods has been determined only by laboratory simulations. In the laboratory, ideal conditions are created; that is, the position of the ball within the cup, the position of the x-ray beam, the quality of the radiograph, and the position of the so-called phantom apparatus with respect to the x-ray beam are all controlled and reproduced with a high level of accuracy and precision from one radiograph to the next. In contrast, conventional clinical radiographs inevitably involve variations in the exposure of the film, beam source-to-film distance, rotation of the lower extremity, and other variables. The purpose of the present study was to measure and compare the accuracy of computerized edge-detection methods and that of manual methods, with use of the true amount of wear as a basis.

Materials and Methods

Laboratory Simulation of Radiographic Wear

An apparatus was constructed to position the femoral ball within an acetabular shell and to displace the femoral ball in three dimensions by arbitrary amounts (Fig. 1). The ball could be moved in axial (superior-inferior), mediolateral, and anteroposterior directions independently, with use of three dial micrometers, each with a resolution of 0.01 mm. The cup, in turn, could be rotated in two planes and fixed in any desired combination of abduction and anteversion. A Harris-Galante porous ingrowth acetabular shell and a 28-mm-diameter Harris-Galante cobalt-chromium-alloy femoral ball (both from Zimmer, Warsaw, Indiana) were mounted onto the apparatus. The distance between the beam source and the femoral ball was 100 cm, with the film 12 cm below the femoral ball center. The ball center was positioned 5 cm superior and 7 cm lateral to the beam source, simulating a typical radiograph of both hips.

Nine orientations of the cup were included and combined three values of abduction (20°, 45°, or 55°) and three values of anteversion (0°, 10°, or 20°). For each of the nine combinations of abduction and anteversion, thirteen different random three-dimensional wear vectors were generated. The random wear vectors had components within 0.5 and 4.5 mm in the superior direction, between 0.0 and 3.0 mm in the medial direction, and between –3.0 and 3.0 mm in the anteroposterior direction. A total of 117 values of wear were simulated. The resultant vectors of simulated wear (ball displacement in three-dimensional space) were between 0.5 and 5.18 mm, with a mean of 2.65 mm, a median of 2.78 mm, and a variance of 1.67 mm.

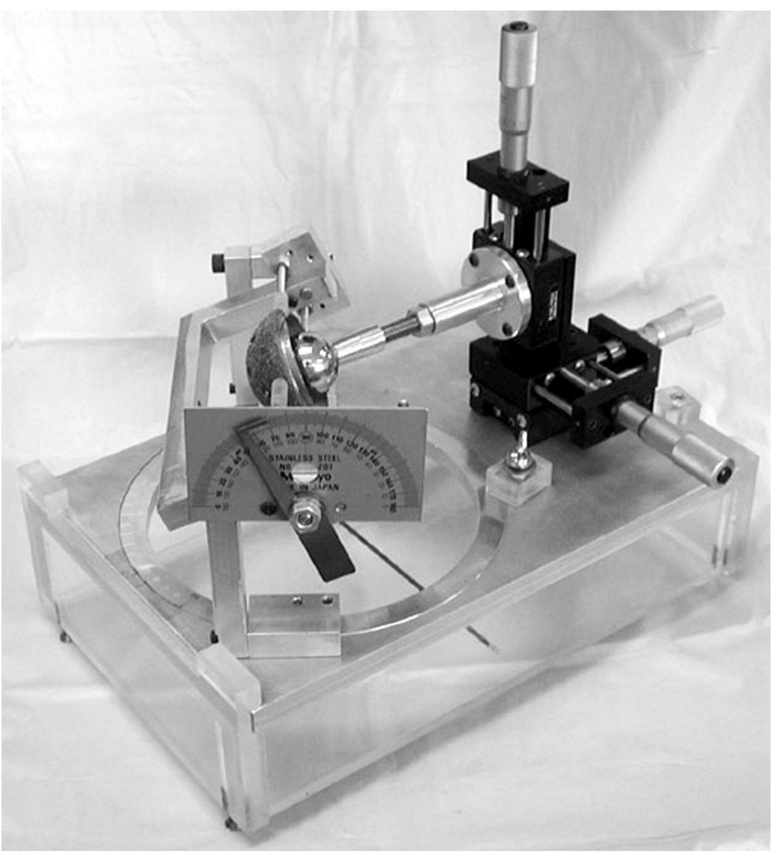

Fig. 1
The phantom apparatus that was used for creating the different three-dimensional displacements of the ball within the cup, simulating different magnitudes and directions of wear.

With each of the nine cup positions, the ball was first positioned such that it was centered in the acetabular shell with the aid of a dummy liner. The dummy liner was then removed, and a radiograph was made, simulating the immediate postoperative radiograph with zero wear. Then, each of the thirteen random values of wear were simulated by displacing the ball within the acetabular shell with use of the dial micrometers, and a new radiograph was made with each ball position, for a total of fourteen radiographs (the zero-wear radiograph and the radiographs made with the ball in thirteen random positions). This was repeated with each of the nine orientation combinations, for a total of 126 radiographs (117 wear vectors and nine zero-wear radiographs).

The three-dimensional computerized wear measurement methods required cross-table lateral radiographs as well as anteroposterior radiographs. It was not practical to tilt the apparatus by 90° to make cross-table lateral radiographs because the hardware would obscure the cup. Instead, for each of the 126 cup wear vectors, a second vector and cup position were calculated, such that an equivalent of a cross-table lateral radiograph could be made without tilting the apparatus. As a result, unlike clinical radiographs, the laboratory radiographs were the same quality in both anteroposterior and lateral planes.

In all, 126 anteroposterior and 126 cross-table lateral radiographs were made, with use of the laboratory radiograph system (Faxitron 43805N Series X-ray; Hewlett-Packard, Palo Alto, California).

Retrieved Acetabular Liners

Fourteen polyethylene acetabular liners retrieved during revision operations were randomly selected retrospectively from the collection of the senior author (L.D.D.). The revision operations had been performed at seventy to 212 months after implantation (average, 126 months). Postoperative radiographs and the radiographs that were made immediately prior to the revision operation were used to measure wear. The acetabular cups were all metal-backed with porous ingrowth shells (eight different designs), and the ball diameters ranged from 24 to 32 mm.

The interior surface of each retrieved cup was measured over an evenly distributed matrix of 301 points, with use of a coordinate measuring machine (BRT 504; Mitutoyo America, Aurora, Illinois) with a touch probe (TP200; Renishaw, Gloucestershire, United Kingdom) fitted with a 4-mm ruby stylus (Mitutoyo America). These digitized data points were then imported into a software package (Qualstar 2.0H; ICAMP, Los Alamos, New Mexico). With use of this software and a least-squares regression algorithm, a spherical model was interactively fit to the data from the nonworn regions. Deviation of the data from the spherical model in the worn regions indicated the local depth of wear. This technique has been validated in hip-joint simulator studies[14].

Methods of Radiographic Wear Measurement

Wear was measured from radiographs with use of three commonly used manual measurement methods and two computerized methods. The computerized methods featured both two-dimensional and three-dimensional measurement capabilities. The two-dimensional methods required only anteroposterior radiographs, whereas the three-dimensional methods required both anteroposterior and cross-table lateral radiographs. The manual methods were the Charnley duoradiographic method[15], the Livermore method[3], and the Dorr and Wan method[6]. The computerized methods were the PolyWare technique (Draftware Developers) and the Hip32 Hip Analysis Program (University of Chicago Medical Center).

For the computerized methods, the radiographs were scanned with a transmission-light scanner (PowerLook II; UMAX Technologies, Fremont, California) at 200 dots per inch, with a 256-level gray scale and at 100% magnification. Image files were stored without compression. All scanning and measurements were performed according to the instructions specified by each software manual. All radiographs were scanned before any manual methods were used.

With the phantom model, all seven methods of wear measurement could be tested. However, because of poor contrast between the femoral ball and acetabular shell with some of the clinical radiographs, the Charnley duoradiographic method could not be used[16]. Therefore, this method was omitted from the clinical section of the study. Additionally, the three-dimensional features of both computerized methods could not be included because there was not sufficient contrast between the femoral ball and the acetabular shell in the cross-table lateral radiographs for most of the retrieved liners. However, the Livermore method, the method of Dorr and Wan, and the two-dimensional measurements of PolyWare and Hip32 were used on all anteroposterior clinical radiographs, since these methods evaluated the distal-inferior portion of the ball outside the acetabular cup.

Data Analysis

Each measurement of wear was subtracted from the corresponding true value of wear to calculate the error. With the phantom model, the true value was known by the position of the dial micrometers. With the retrieved implants, the true wear was the measurement made with use of the coordinate measuring machine. Then, we used the absolute values of these errors to compare the methods. For the errors calculated with each method, the median of the absolute values and the maximum, minimum, and standard deviation were calculated and plotted. Medians, as opposed to means, were used for analysis because the errors were not normally distributed. The observer who measured all radiographs was blinded to the true wear values. The Kruskal-Wallis method and the Mann-Whitney U test were used to determine the certainty that each observed difference among the methods was obtained by chance alone (the p value).

The distribution of errors was not normal (Fig. 2). Typically, the mean was somewhat greater than the median, and the median was a better representation of the sample. For this

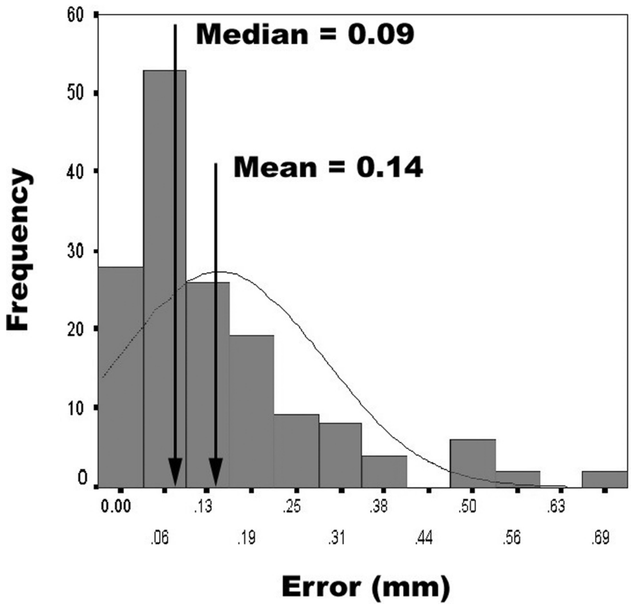

Fig. 2
The distribution of errors with the PolyWare two-dimensional method was typical of the distribution of errors found in this study.

reason, we used box plots and nonparametric statistics in addition to the means. Box plots are good representations of the entire distribution of data because they show the minimum, 25th percentile, 50th percentile (the median), 75th percentile, and the maximum.

Results

Phantom Model

With the phantom model, median errors were 0.1 mm with the Livermore method and both computerized methods, and they were 0.23 mm with the Charnley method. The Dorr and Wan method had the greatest error, with a mean and median of >1.7 mm and a maximum of >4 mm (Fig. 3). This appeared logical because the direction of wear was random, whereas the Dorr and Wan method inherently assumes wear to be at a small angle relative to the cup face.

In general, the error in the measurement of wear was not dependent on the orientation of the acetabular cup. Specifically, only two methods showed a significant trend ($p < 0.05$) when compared by cup orientation. PolyWare with the three-dimensional feature had greater errors with 20° of abduction and 0° of anteversion. The median error for this combination of abduction and anteversion was still <0.25 mm, but the median errors for all other angles were <0.15 mm. In contrast, the three-dimensional version of Hip32 had smaller errors for that particular combination of 20° of abduction and 0° of anteversion.

In addition to cup orientation, the accuracies of the seven wear estimation methods were compared with the amount of true wear that was being simulated by the phantom apparatus (see Appendix). The amount of linear wear was divided into three categories: <2 mm, 2 to 4 mm, and >4 mm. Three of the seven wear methods tested showed bias for different amounts of wear ($p < 0.001$). The Livermore method was more accurate for greater amounts of true wear (smaller percentage of error), whereas the Dorr and Wan method and the three-dimensional version of Hip32 were more accurate for smaller amounts of wear.

Clinical Radiographs

We were able to measure wear from the clinical radiographs of patients with use of the Livermore, Dorr and Wan, PolyWare (two-dimensional), and Hip32 (two-dimensional) methods. On the other hand, to assess true wear, direct measurement of wear from the retrieved liners was done with use of the coordinate measuring machine. With direct measurements, wear had a median of 2.18 mm (range, 0.35 to 4.75 mm), similar to that simulated with our laboratory phantom model.

There was a substantial difference between the phantom model and the clinical radiographs with respect to the accuracy of the wear methods (Fig. 4). Whereas the Dorr and Wan method had a significantly greater error than other methods with the phantom model ($p < 0.001$) (Fig. 3), there was little difference between the medians of the two manual and two computerized

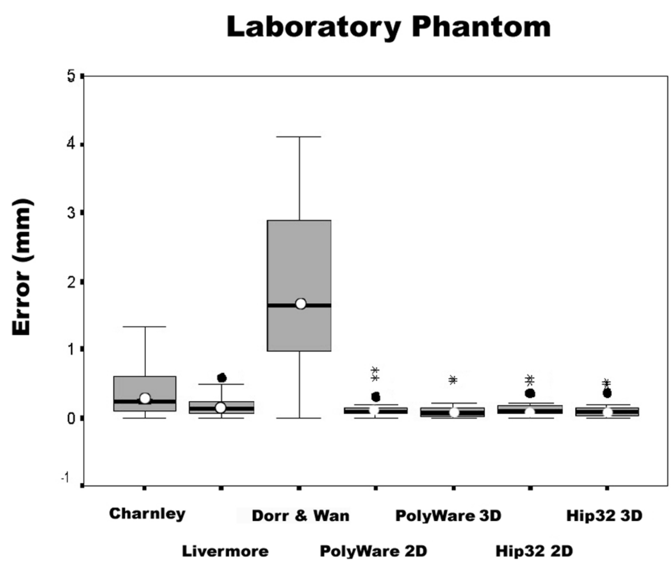

Fig. 3
Box plots represent the errors of radiographic measurements made with use of the phantom apparatus. The true value of wear was known by the displacement of the ball and was subtracted from each measurement. The median of the absolute values of these errors is shown by the thick horizontal line within each box. The bottom and top of the box represent the 25th and the 75th percentile. The whiskers represent the high and the low values, excluding the outliers between 1.5 and 3.0 box lengths from the median. Outliers beyond this range are plotted individually; therefore, the maximum error is always apparent. The mean is also represented by a small white circle inside the box.

TABLE I P Values for Comparison of Errors with the Phantom Model*

	Livermore	Dorr and Wan	PolyWare 2-D	PolyWare 3-D	Hip32 2-D	Hip32 3-D
Charnley	0.002	<0.001	0.001	0.001	0.007	0.003
Livermore		<0.001	0.87	0.7	0.26	0.89
Dorr and Wan			<0.001	<0.001	<0.001	<0.001
PolyWare				0.75	0.23	0.82
PolyWare					0.14	0.61
Hip32						0.38

*The p values were obtained with the Mann-Whitney U test in a comparison of the absolute values of errors associated with the seven methods. 2-D = two-dimensional, and 3-D = three-dimensional.

methods with clinical radiographs (Fig. 4). Indeed, with clinical radiographs, the maximum error for the Dorr and Wan method was smaller than that with the Livermore or PolyWare methods. The median errors of the clinical measurements were 0.6 mm (range, 0 to 1.8 mm) for the Dorr and Wan method, 0.4 mm (range, 0.1 to 2.5 mm) for the Livermore method, 0.4 mm (range, 0 to 2.2 mm) for the PolyWare technique, and 0.2 mm (range, 0 to 1.8 mm) for the Hip32 method.

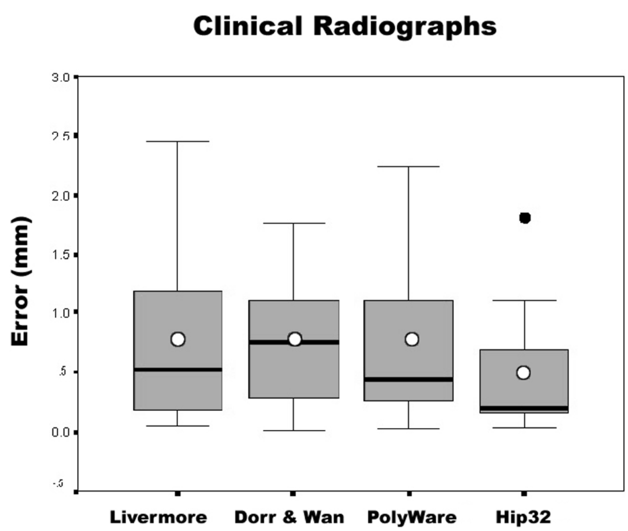

Fig. 4
Box plots represent the errors of radiographic measurements made with use of clinical radiographs. The true value of wear was assumed to be that directly measured with the coordinate measuring machine from the retrieved components and subtracted from each measurement to calculate error. The median of the absolute values of these errors is shown by the thick line within each box. The bottom and top of the box represent the 25th and 75th percentiles. The whiskers represent the high and the low values, excluding the outliers between 1.5 and 3.0 box lengths from the median. Outliers beyond this range are plotted individually; therefore, the maximum error is always apparent. The mean is also represented by a small white circle inside the box.

For all four methods of wear measurement, the percentage of error was dependent on the magnitude of true wear as measured directly by the coordinate measuring machine (see Appendix). Although the smaller amounts of wear had larger *percentages* of error, all actual errors were so small that none of the differences were significant ($p > 0.41$ for all).

Comparison of the Phantom Model and Clinical Radiographs

The p values that were obtained with the Mann-Whitney U test in the comparison of the errors for the phantom model measurements are shown in Table I, and those obtained in the comparison of the clinical radiographs and the measurements of the retrieved components are shown in Table II. P values of ≤0.05 were considered to be significant.

With the phantom model, all of the methods tended to underestimate wear, on the average, by 0.02 mm (PolyWare two-dimensional method) to 0.08 mm (Hip32 two-dimensional method) and by 1.8 mm with the Dorr and Wan method. In contrast, with the clinical radiographs, the Livermore, PolyWare, and Hip32 methods overestimated wear, on the average, by 0.25, 0.18, and 0.20 mm, respectively, whereas the Dorr and Wan method underestimated wear by an average of 0.32 mm.

Discussion

Previous studies that have assessed the accuracy of computerized techniques for the measurement of wear from total hip replacement radiographs have done so with use of phantom models and well-controlled laboratory conditions[9,10,13,17]. Our laboratory study of manual and computerized methods with use of a phantom model had median errors of 0.14 to 0.17 mm for accuracy. This is in general agreement with other reported accuracies of computerized methods tested with laboratory phantom models, which have averaged from 0.08 to 0.19 mm[9,10,13,17].

In contrast, with clinical radiographs, the median error was between 0.2 and 0.6 mm, which is substantially greater than that found with the phantom model. This margin of error occurred with both computerized and manual measurements from clinical radiographs. Compared with the computerized

TABLE II P Values for Comparison of Errors with Clinical Radiographs*

	Dorr and Wan	PolyWare	Hip32
Livermore	0.87	0.8	0.52
Dorr and Wan		0.76	0.3
PolyWare			0.42

*The p values were obtained with the Mann-Whitney U test in a comparison of the absolute values of the errors associated with the four methods. Only the two-dimensional versions of the computerized methods could be used because of the poor contrast of cross-table lateral radiographs.

methods, the two manual measurement methods were simpler to use and were performed rather easily on poor contrast clinical radiographs, even when the femoral ball margins were partially obscured. This is in agreement with the study by Barrack et al.[18], who concluded that, with clinical radiographs, the Dorr and Wan method is probably the simplest to apply.

Few studies have validated the computerized methods of wear measurement made with clinical radiographs. Ohlin et al.[19,20] found an average error of 1.1 mm and a maximum error of 1.9 mm in a comparison of measurements of retrieved cups made with a coordinate measuring machine and those made with a computerized radiographic method without automatic edge-detection. The average error in their studies was greater than the median error of 0.2 to 0.4 mm that we found with edge-detection methods, but the maximum errors were comparable.

Recently, Barrack et al.[18] compared wear measurements from the radiographs of twenty-one hips with direct measurements of the retrieved polyethylene liners. Their finding was consistent with ours in that the manual methods of Livermore and of Dorr and Wan were comparable with those of the computerized methods. However, the errors in their study were nearly ten times greater than ours. Despite the differences in the techniques that were used, neither our study nor theirs found that computerized methods were superior to manual methods as has been inferred from laboratory studies[18-20].

Although it would be expected that computerized methods outperform manual methods in intraobserver and interobserver reproducibility, both computerized packages were difficult to learn. The cost of the software, as well as the necessity for a dedicated computer, scanner, and personnel to operate the equipment must be considered. Experience with the software was necessary to correct the automated edge-detection routines in many cases. Furthermore, lateral radiographs with good contrast are necessary in order to use the three-dimensional software features.

The computerized methods function by modeling the margins of the ball and the acetabular shell, each with a fitted ellipse. Therefore, the accuracy of these methods depends on the level of contrast at these margins and how much of each margin is unobscured. Likewise, the Livermore method uses circular templates that are fitted to the visible portion of the femoral ball, and it also depends on this contrast level. In contrast, the Dorr and Wan method uses only the edges of the ball along the face of the cup, which nearly always has good contrast, making this the easiest method to use.

For the evaluation of new bearing materials in a clinical trial, and in research and academic environments where the highest accuracy possible is required, the Hip32 method by Martell and Berdia provides the lowest median error, 0.2 mm. On the other hand, the Livermore method and the Dorr and Wan method had median errors of <0.6 mm and are easy to use. For routine wear measurements in clinical practice, these manual methods are inexpensive and are perhaps the most straightforward way to measure wear. Given the simplicity of application, we consider these two methods to have satisfactory accuracy and they should perhaps be used for routine clinical wear measurements.

Appendix

(eA) Bar graphs showing the percentage of error as a function of magnitude of true wear as simulated in the laboratory phantom model and as measured directly from the liners are available with the electronic versions of this article, on our web site at www.jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM). ■

NOTE: The authors thank Edwin Mirzabeigi, MD, for his help with the project.

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In support of their research or preparation of this manuscript, one or more of the authors received grants or outside funding from Centerpulse Orthopedics, Austin, Texas. None of the authors received payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity. No commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, educational institution, or other charitable or nonprofit organization with which the authors are affiliated or associated.

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