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Short communication

Accuracy evaluation of a lower-cost and four higher-cost laser scanners

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ABSTRACT

Knowing the accuracy of laser scanners is imperative to select the best scanner to generate bone models. However, errors stated by manufacturers may not apply to bones. The three objectives of this study were to determine: 1) whether the overall error stated by the manufacturers of five laser scanners was different from the root mean squared error (RMSE) computed by scanning a gage block; 2) the repeatability of 3D models generated by the laser scanners when scanning a complex freeform surface such as a distal femur and whether this differed from the repeatability when scanning a gage block; 3) whether the errors for one lower-cost laser scanner are comparable to those of four higher-cost laser scanners.

The RMSEs in scanning the gage block were 2 to 52 μm lower than the overall errors stated by the manufacturers. The repeatability in scanning the bovine femur 10 times was significantly worse than that in scanning the gage block 10 times. The precision of the lower-cost laser scanner was comparable to that of the higher-cost laser scanners, but the bias was an order of magnitude greater. The contributions of this study are that 1) the overall errors stated by the manufacturers are an upper bound when simple geometric objects like a gage block are scanned, 2) the repeatability is worse on average three times when scanning a complex freeform surface compared to scanning the gage block, and 3) the main difference between the lower-cost and the higher-cost laser scanners is the bias.

1. Introduction

Laser scanning is used to create three-dimensional (3D) bone models for applications related to orthopedics and historic heritage (Popov and Onuh, 2009; Verim et al., 2013; Kuzminsky and Gardiner, 2012; Yeon Cho, 2011). A 3D laser scanner is composed of the laser sensor, which determines the distance between the laser source and the surface of the object being scanned by triangulation, and the motion tracking device that determines the position and orientation of the laser sensor or of the object in 3D space. The most recent 3D laser scanners are handheld, which use as motion tracking devices either a manual articulating measuring arm or a stereo-photogrammetric system. Among the advantages of the handheld laser scanners over the traditional 3D desktop scanners are manual control of the scanning process and real-time viewing of the 3D data generated because the motion tracking of the laser sensor is instantaneous; hence registration need not be performed in post-processing between scans taken from different views of the object as with desktop scanners.

Knowing the accuracy of laser scanners is imperative to select the best scanner to create 3D bone models. However, the only available information about the accuracy of these scanners is the error value stated by the manufacturer. This value is obtained using test standards that require the scanning of gage blocks or ball bars, and manufacturers often report separate error values for the laser sensor and the motion tracking device. When overall system error is reported, this is often obtained with a custom test or with non-uniform test standards, making it difficult to compare the errors stated from different manufacturers. Moreover only the German standard VDI/VDE 2617-6.2 was specifically created for laser scanners, while the more commonly used international ISO 10360 and American ASME B89.4.22 standards were created for tactile coordinate measuring machines which are influenced by different sources of error than laser scanners. For this reason, some studies tried to develop specific methodologies to perform verification of laser scanners (Acko et al., 2012; Carmignato, 2009).

Because the accuracy of laser scanners depends on the shape, texture, and material reflectivity of the object being scanned, and because various test standards or custom tests are used by manufacturers to assess the error, the overall error value stated by manufacturers may not apply to bones. Hence, one objective of this study was to determine whether the overall error of five commercially-available portable laser scanners stated by the

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manufacturers using non-uniform standard or custom tests was different from the error in scanning a gage block. A second objective was to determine the repeatability of the 3D models generated by laser scanners when scanning a complex freeform surface such as a distal femur and to determine whether this differs from the repeatability when scanning an object with a simple shape like a gage block. A third objective was to determine whether the errors of one popular lower-cost laser scanner are comparable to those of four higher-cost laser scanners.

2. Methods and materials

The five laser scanners selected for this study (Table 1) were produced by five different manufacturers: Nikon™ (Nikon), Laser Design Inc.™ (LDI), Creaform™ (Creaform), Northern Digital™ (NDI), and NextEngine™ (NextEngine). The first four scanners are higher-cost laser scanners (priced above $70,000 US) and were selected because the overall error stated by the manufacturers was among the lowest for laser scanners that allow the scanning of objects of the size of a long bone. The last scanner (NextEngine™) was selected because it is a popular lower-cost laser scanner (priced below $10,000 US) used in many orthopedic applications.

The same ceramic gage block (100 mm long, 0-grade, Mitutoyo, Japan) and bovine distal femur specimen were sent to each manufacturer of a higher-cost laser scanner. The distal femur was selected because of its complicated morphology, so that the results found for the femur can be translated to other bones in the body.

Prior to sending the specimen, the frozen femur was thawed for 24 h and dissected to remove soft tissues. Four spherical fiducial markers with a 16 mm diameter were attached to the bone to enable a precise registration of the bone models. Next, the bone was submerged in 6% sodium hypochlorite solution for 10 h to remove the articular cartilage, dried by oven-cooking for 2 h at 180 °C, sterilized, and potted into a hollow metal cylinder (Fig. 1A).

Each manufacturer scanned the gage block and the specimen 10 times each using settings they believe would produce the most accurate 3D models. The 10 scans of the specimen and the 10 scans of the gage block were sent to the authors in stereolitography format (STL, Fig. 1B and C). The same bovine femur and gage block also were scanned 10 times each by the authors using the popular low-cost laser scanner in Wide mode with a resolution of 17,000 points per scan and in 40° increments for each turntable rotation.

For each scanner, the error for the gage block was computed as the difference between the length of the gage block measured as the distance between two parallel planes best fit to the shortest sides of the 3D model and the calibrated length. Next, the bias (i.e. systematic error) and the precision (i.e. random error) were computed for each scanner as the mean and standard deviation respectively of the errors computed for the 10 scans. The root mean squared error (RMSE) was computed as:

$$\mathrm{RMSE}_{\mathrm{GageBlock}} = \sqrt{\mathrm{bias}^2 + \mathrm{precision}^2} \tag{1}$$

For each laser scanner, the repeatability of the 3D femur models was quantified as the difference in the shape of the 10 3D femur models with comparisons between all pairs of the 10 models (i.e. 45 comparisons for each laser scanner) using Geomagic (3D System, USA) as described in Fig. 2. For each of the 45 comparisons, the root mean square difference (RMSD) between the morphology of the two bone models was computed. The repeatability of the 3D femur models was the mean RMSD (Eqs. (2) and (3)).

$$\text{Mean RMSD} = \frac{\sum_{i=1}^{45}\left(\sqrt{\frac{1}{n}\sum_{j=1}^{n} D_j^2}\right)_i}{45} \tag{2}$$

Table 1
Specifications for the four higher-cost laser scanners. The specifications for the NextEngine™ are different from the specifications of the higher-cost laser scanners because it is a desktop laser scanner which typically includes the actual laser scanner and a turntable (optional) that can rotate about its vertical axis and that supports the object during scanning. This desktop 3D scanner works in two modes: Macro and Wide. Each mode presents a different field of view and accuracy, with the Macro-mode yielding the lowest scanning errors according to the manufacturer specifications (maximum error is $\pm$0.13 mm in Macro-mode and $\pm$0.38 mm in Wide mode). In this study, Wide mode was used because it is the mode with a field of view (345 × 258 mm^2) large enough to scan a long bone. The specifications for this laser scanner include a resolution of 22,500 points per square inch in Wide mode, and 50 kHz processed points/s.

Tracker type		Tracker characteristics	Laser sensor type	Laser sensor characteristics
Nikon™	Arm MCA 30	7 axis arm – 3 m diameter measuring volume	MMDx50	0.05 mm point-to-point resolution – 50 mm line width
LDI™	Arm Space Arm 3.2	6 axis arm – 3.2 m diameter measuring volume	SLP-250	0.03 mm max point-to-point resolution – 20 to 25 mm line width
NDI™	Stereophotogrammetry Pro CMM 1000	3 cameras – 10 m^3 measuring volume – active markers	ScanTrack	0.01 mm mean point-to-point resolution – 93 to 140 mm line width
Creaform™	Stereophotogrammetry C-Track 780	2 cameras – 7.8 m^3 measuring volume – passive markers	Metrascan 3D 70	multistripe laser sensor with 2 crossed lines – 70 mm × 70 mm laser cross-area – 0.05 mm point-to-point resolution

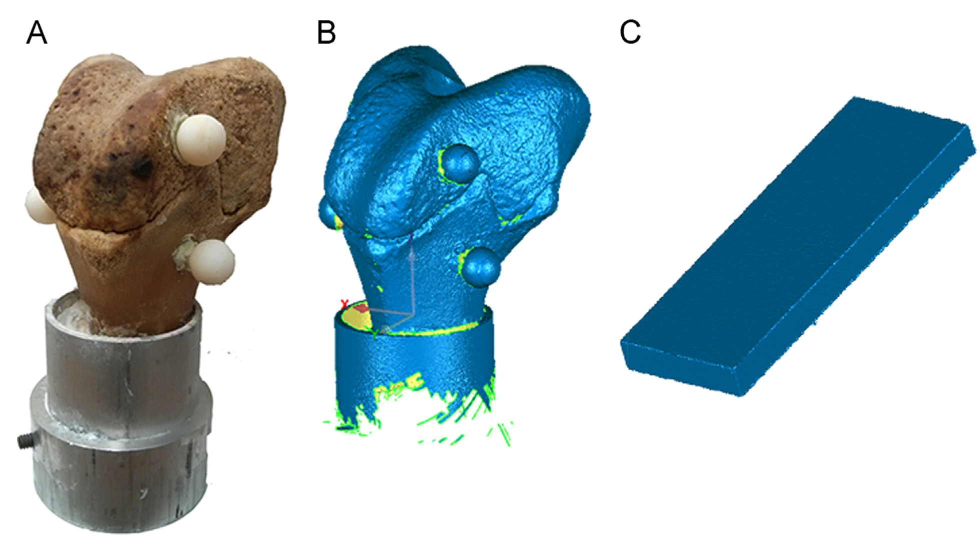

Fig. 1. Bovine femur specimen with fiducial markers (A), corresponding 3D bone model generated with one of the laser scanners (B), and 3D model of the gage block generated with one of the laser scanners (C). A non-human femur was chosen to easily ship the specimen outside the country.

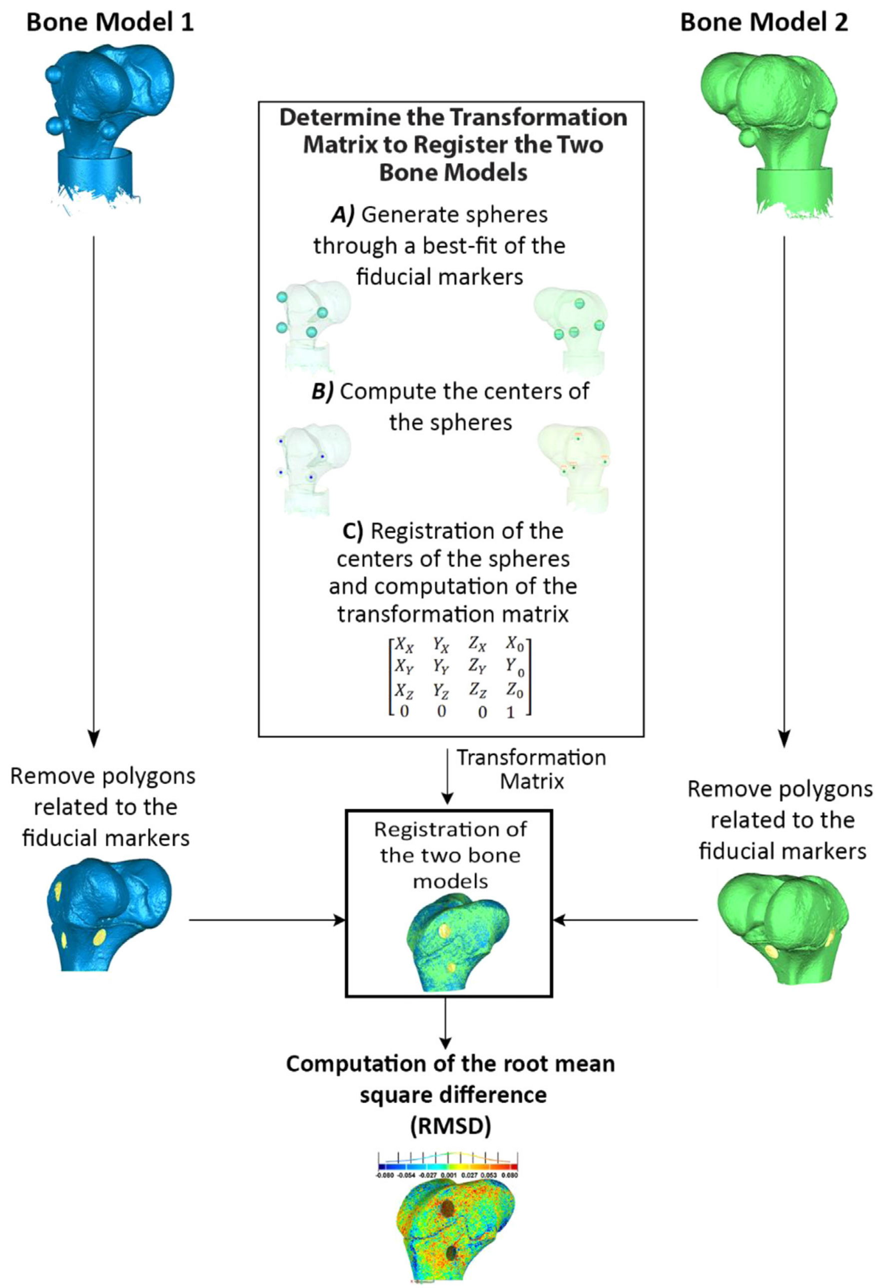

Fig. 2. Method used to compare two bone models. The paired 3D femur models were registered using the centers of the spheres obtained through a best-fit (i.e. least squares method) of the fiducial markers. Next, in each 3D femur model the polygons corresponding to the fiducial markers, to the area of attachment of the markers, and to the metal cylinder were removed to limit the repeatability analysis to the bone surface only. The bone models were registered using the transformation matrix obtained from registering the centers of the fiducial markers, and the difference between the two bones models were computed in terms of differences in point-to-point distances. Because the removed areas on the bone surface did not correspond precisely among the 3D femur models, the highest differences between two bone models were always found in those locations. Hence, to exclude these differences from the final result, an upper limit of 1 mm was set for the computation of the difference so that only the differences below 1 mm were analyzed.

$$D_j = \sqrt{(x_j - \hat{x}_j)^2 + (y_j - \hat{y}_j)^2 + (z_j - \hat{z}_j)^2} \quad (3)$$

where D_j is the difference in distance between the j-point on the test model with coordinates $x - y - z$ and the corresponding closest point on the reference model with coordinates $\hat{x} - \hat{y} - \hat{z}$, and n is the total number of points on the test model.

To compare the repeatability for the femur to that of the gage block, the RMSDs were computed for the gage block using the same methodology as that for the femur. The only exception was that the registration of the 3D models of the gage block was performed using the iterative closest point algorithm implemented in Geomagic (i.e. shape match) because applying fiducial markers on the surface of the gage block would have covered much of the surface available for scanning. A Students *t*-test determined whether the mean RMSD for the bovine femur was different from the mean RMSD for the gage block for each laser scanner.

The overall error stated by the manufacturers was obtained using the ISO 10360-2-2009 for the NDI™ scanner, the ASME B89.4.22-2004 for the LDI™ and Creaform™ scanners, and custom tests for the Nikon and NextEngine™ scanners (See Appendix).

3. Results

The RMSEs from scanning the gage block were 2 to 52 μm lower than the overall errors stated by the manufacturers (Table 2). Indeed, the ranking order of the laser scanners is the same when considering the RMSE for the gage block and the

Table 2
Length errors and 3D model repeatability (as quantified by the mean RMSD) of the laser scanners for the gage block, 3D model repeatability for the bovine femur, and overall error stated by the manufacturers.

	Gage block length errors and 3D Model repeatability				Bovine femur 3D model repeatability	Manufacturer overall errors	
	Bias (μm)	Precision (μm)	RMSE (μm)	Mean RMSD (μm)	Mean RMSD (μm)	Overall error (μm)	Test type
Nikon™	33.5	9.1	34.7	29.6	69.7	54	CUSTOM TEST
LDI™	−19.3	35.8	40.7	27.0	97.2	60	ASME.B89.4.22
NDI™	70.9	13.1	72.1	28.4	79.6	80	ISO 10360-2-2009
Creaform™	−81.0	17.6	82.9	29.2	66.8	85	ASME.B89.4.22
Next Engine™	325.9	34.3	327.7	29.7	76.2	380	CUSTOM TEST

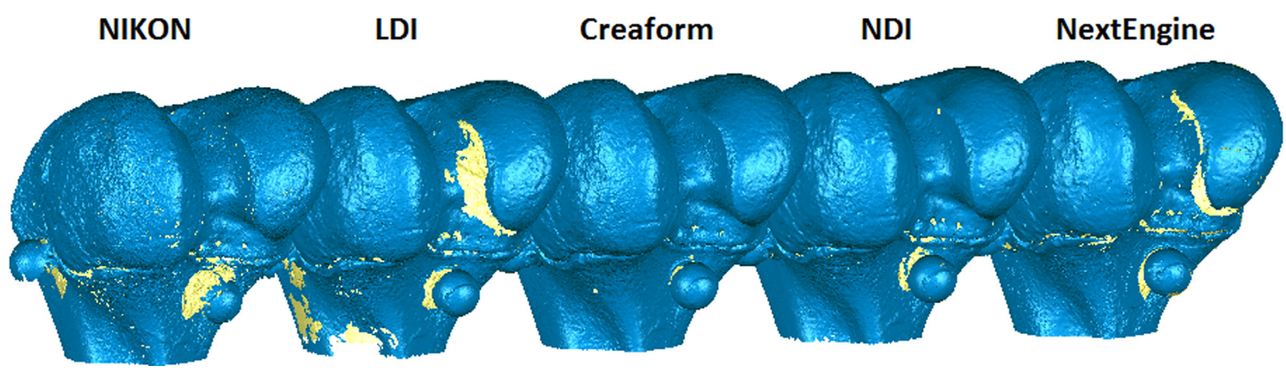

Fig. 3. Examples of the 3D bone models of the distal bovine femur generated with each of the five laser scanners. The yellow areas (or light gray areas for the printed version of this article) are holes in the models (backfaces). Typically holes at the site of attachment of the markers were present in the 3D models generated with all five laser scanners, but for LDI and NextEngine several holes were present also in other areas close to the posterior condyles.

overall error stated by the manufacturers, with the arm-based scanners having higher accuracy than the stereophotogrammetry-based systems because of lower bias.

The mean RMSD for the femur and gage block ranged between 67–97 μm and 27–30 μm for all laser scanners, respectively. For each laser scanner, the mean RMSD for the bovine femur was significantly higher than the mean RMSD for the gage block ($p < 0.0001$ for all scanners).

The precision for the lower-cost scanner was comparable to that of the higher-cost laser scanners but the bias ranged from 4 to 17 times greater. Qualitatively, all bone models had a closed surface except those from the LDI™ and NextEngine™ 3D models which had some holes in the most concave areas of the femur (Fig. 3).

4. Discussion

The key findings of our study were that 1) the RMSEs in scanning the gage block were lower than the overall errors stated by the manufacturers, 2) the mean RMSD for the bovine femur was significantly higher than the mean RMSD for the gage block for all laser scanners, 3) the precision of the lower-cost laser scanner when scanning the gage block was comparable to that of the higher-cost laser scanners, but the bias was an order of magnitude greater.

Two methodological issues should be discussed. One concerns the gage block material which was ceramic. As such, the material was translucent and can let the laser light slightly penetrate the surface, thus potentially introducing measurement error. Nevertheless, the RMSEs were lower than the overall errors stated by the manufacturers (Table 2). One reason could be that the gage block was scanned only in the center of the measurement volume where laser scanners produce better measurements and not at the limits as required by the test standards.

A second methodological issue concerns the use of different registration methods. As mentioned earlier, the bone models in the paired comparisons were registered using the fiducial markers whereas the gage block models were registered using the iterative closest point algorithm implemented in Geomagic. For each of the five laser scanners, the mean RMSD was computed using the iterative closest point algorithm for 5 bone models. Results for this method were comparable to those obtained using fiducial markers.

The higher-cost arm-based laser scanners were more accurate than the higher-cost stereophotogrammetry-based scanners because they had less bias (Table 2). This might be explained by considering that stereophotogrammetry-based scanners are more complex than arm-based scanners and so subject to more sources of systematic error (e.g. lens distortions, stereo set-up distortions, errors in the transformation of an imaged marker into its geometric coordinate; Chiari et al., 2005; Weng et al., 1992).

The repeatability in the 3D models generated with a laser scanner depends on the shape of the object being scanned. The 3D model obtained when scanning a complex freeform surface such a distal femur was less repeatable than the 3D model obtained when scanning a gage block. Thus to thoroughly evaluate a laser scanner for a particular application, it would be prudent to perform an analysis similar to that performed herein for the bovine femur. Only in this manner can the repeatability for the application of interest be known. Specifically, we recommend using a quantity like the mean RMSD which is more suitable to assess the variability in surface morphology between two 3D models than the precision which is more appropriate to quantify differences in a particular dimension.

Finally, the RMSE of the popular lower-cost laser scanner was over 200 μm greater than that of higher-cost laser scanners and this difference was mainly due to difference in bias rather than difference in precision. How the bias influences results should be assessed prospectively on a case-by-case basis.

Because the technology of laser scanners changes over time with new designs coming on line regularly every 5 years or so, the long-term contributions of this study should be considered. One is that the overall error stated by the manufacturers represents an upper bound when simple geometric objects (e.g. gage block) are scanned near the center of the measurement volume. However, the repeatability (i.e. mean RMSD) of the 3D models generated by these laser scanners is worse on average three times when scanning a complex freeform surface. Undoubtedly the mean RMSD will decrease with technology advances but even so the need to evaluate the repeatability prospectively on a case-by-case basis will be necessary until such time as the repeatability becomes independent of the shape of the surface being scanned. The main difference between the lower-cost and the higher-cost laser scanners is the much greater bias for the lower-cost scanner, while the precision is comparable. Because of the high bias of the lower-cost scanner, it is necessary to quantify the bias prospectively for each new design and assess the impact of this error on the application of interest.

Conflict of interest statement

The authors have no personal or financial conflict interest that influenced this work.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2015.11.015.

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