Precision, repeatability and accuracy of Optotrak® optical motion tracking systems

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Abstract: In the field of biomechanics, optical motion tracking systems are commonly used to record human motion and assist in surgical navigation. Recently, motion tracking systems have been used to track implant and bone motion on a micron-level. The present study evaluated four different Optotrak® motion tracking systems to determine the precision, repeatability and accuracy under static testing conditions. The distance between the camera systems and the rigid body, as well as the tilt angle of the rigid body, did affect the resulting precision, repeatability and accuracy of the camera systems. The precision and repeatability, calculated as the within-trial and between-trial standard deviations, respectively, were less than 30 μm; with some configurations producing precision and repeatability less than 1 μm. The accuracy was less than 0.53% of the total displacement for the in-plane motion and less than 1.56% of the total displacement for the out-of-plane motion.

Keywords: reliability; precision; accuracy; Optotrak®; measurement; motion tracking; human motion; rigid body; bias; optical; active marker; biomechanics; experimental biomechanics; computational biomechanics.

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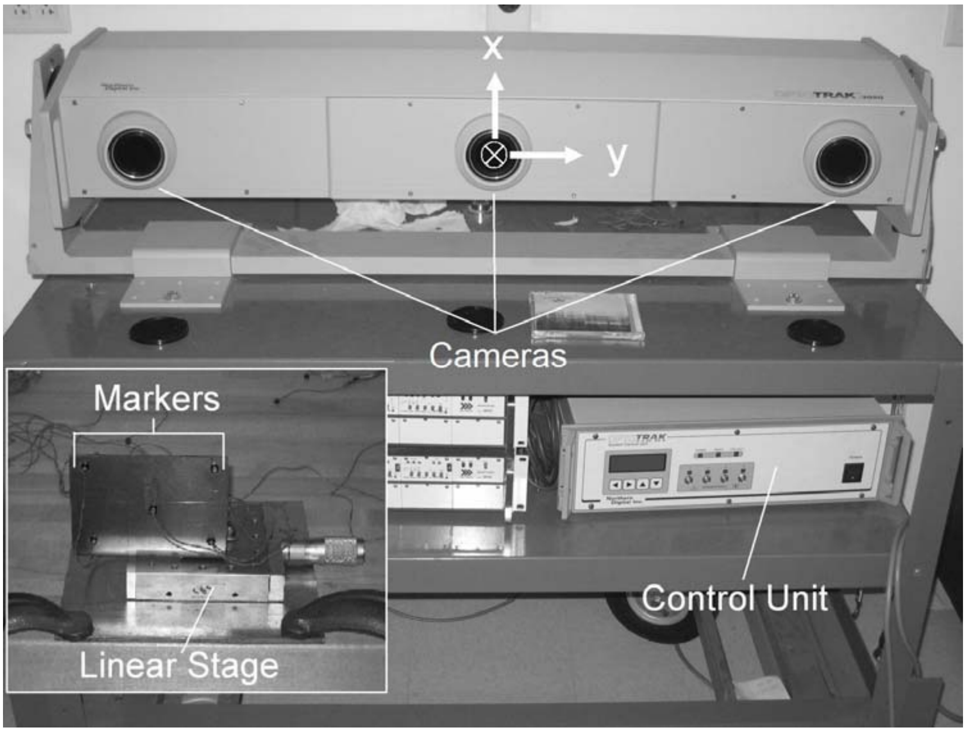
1 Introduction

Optical motion tracking systems have previously been used in a number of studies requiring either large-scale (10 to 1000 mm) or small-scale (1 to 10 mm) tracking of rigid body motion. Within biomechanics, specific large-scale applications include studies on human motor control (Archambault et al., 1999; Corriveau et al., 2001; Esparza et al., 2003) and small-scale applications such as surgical navigation (Higgins et al., 2002; Li et al., 1999; Sugano et al., 2001). Recently, optical motion tracking systems have shown increased use in micron-level studies (0.01 to 1 mm) evaluating implant and bone segment motion (Goel et al., 2005; Higgins et al., 2007; Westphal et al., 2006), but the limitations of motion tracking systems for micron-level assessment have not previously been examined.

The limitations of a motion tracking system may be evaluated through an examination of the precision, repeatability and accuracy (Allard et al., 1995). Previous studies have provided some information as to the limitations of such systems, but a thorough evaluation has not been performed for micron-level assessment. A study from 2006 by States and Pappas reported good repeatability in the Optotrak® 3020 system (NDI, Waterloo, Ontario) with middle focal-length configuration. In addition, they reported a within-trial standard deviation much less than 100 µm for the suggested operating range (States and Pappas, 2006). Numerous motion tracking systems were previously evaluated for accuracy, but with an interest in large-scale motion corresponding to tracking of human movement. A study by Richards (1999) compared seven different motion tracking systems and reported good accuracy in five of the seven systems tested, with typically less than 2 mm root mean square (RMS) error for a moving rigid body and less than 1 mm RMS for a static rigid body. An additional study (Maletsky et al., 2007) evaluated the Optotrak® 3020 system to have accuracy less than 50 µm for both in-plane and out-of-plane motion with an overall translation of 10 mm. Although the previous studies have suggested appropriate precision, repeatability and accuracy of motion tracking systems, evaluation of each direction of motion should be individually evaluated. In addition, the accuracy of the system should be evaluated for translations less than 10 mm. These assessments should include evaluations of the camera system to rigid body distance and tilt of the rigid body away from the plane of the camera system.

The current study evaluated the limitations of three-dimensional (3D) motion tracking systems in order to understand the validity of the results achieved through their use. Specifically, the current study evaluated precision, repeatability and accuracy of four Optotrak® motion tracking systems to provide guidance towards the appropriate applications for use of each camera system.

Figure 1 Middle-focus Optotrak® 3020 system test setup with coordinate system defined



Note: Rigid body with markers and linear stage is shown in bottom left corner.

2 Methods

Four different Optorak® motion tracking systems were evaluated: three Optotrak® 3020 systems calibrated for near, middle and far focal-length, as well as, an Optrotrak® Certus™ far focal length system. Each camera system consists of three cameras mounted rigidly within the apparatus. Calibration of the system was performed by the manufacturer prior to shipment of the device. The operating range for each system, as recommended by the manufacturer, is 1.5 to 3.0 m, 2.0 to 4.0 m, 2.2 to 6.0 m for the near-, middle- and far-focus camera system, respectively. The coordinate system for all the camera systems is defined as shown in Figure 1, with the in-plane motion defined in the x-y plane and out-of-plane motion along the z-axis.

For all tests, four to five markers were placed on a rigid body which measured approximately 100 mm^2 in the plane of the camera. The raw position data from each marker was input into a custom Matlab (The Mathworks, Natick, MA) program to determine the motion of the rigid body. The Matlab program used a sub-program previously developed based on the information of a paper by Sodervist and Wedin (1993). This code has been commonly used in studies which analyse position tracking data of a rigid body (Cereatti et al., 2006; Ianuzzi and Khalsa, 2005; Little and Khalsa, 2005; Reisman and Scholz, 2006) and is readily available through the International Society of Biomechanics software resources (isbweb.org/software/movanal/soder.m).

2.1 Precision

Data were collected for a period of ten seconds at a sampling rate of 50 Hz. Multiple distances between the rigid body and the camera system were evaluated. The distances ranged from 1.5 to 4.5 m, in 0.25 m increments. It should be noted, the three farthest distances were out of the range of the near-focus camera system and the closest distance was out of the range of the Optotrak® 3020 far-focus camera system. The within-trial standard deviations of the static position were reported.

2.2 Repeatability

Similar to the precision testing, data were collected for ten seconds at a sampling rate of 50 Hz. Trials were performed at the same camera system distances as for the precision testing; however, ten repeated trials were conducted at each distance. In addition, at a distance of 3.0 m the affect of tilting the rigid body was evaluated. The rigid body was tilted 0, 40, 60 and 70 degrees away from the plane of the camera system. The between-trial standard deviations of the average position were reported.

2.3 Accuracy

The Optotrak® 3020 system with the middle focal length configuration was evaluated for accuracy. The previously described (Section 2) rigid body was mounted on a linear stage with a resolution of 5 μm (UMR 12.40, Newport, Irvine, CA). The linear stage was advanced in 1 mm increments for a total displacement of 25 mm. At each position, data were collected for ten seconds at a sampling frequency of 50 Hz. The motion of the stage was first aligned with the y-axis to evaluate the in-plane accuracy. Then the motion was aligned with the z-axis to evaluate out-of-plane accuracy. Accuracy was evaluated at three camera system-to-marker distances: 1.5, 3.0 and 4.5 m. The bias, or difference between the expected and measured displacement, was reported for step sizes of 1, 2, 5 and 10 mm.

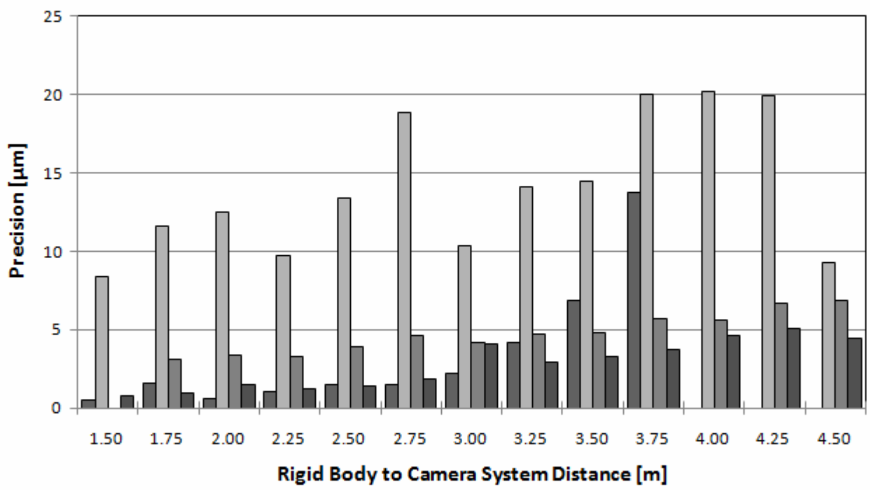
3 Results

Overall, all four systems tested produced precision, repeatability and accuracy under 10 μm when the distance between the camera system and rigid body was minimised within the manufacturer's recommended range.

3.1 Precision

The precision, or within-trial standard deviation, of the position in the x-, y-, and z-directions are reported in Figure 2. The largest standard deviation was seen in the x-direction with the middle-focus camera system, which ranged from 8.4 to 20.2 μm, in comparison to the other systems which ranged from 0.6 to 13.7 μm. The precision of the middle focus 3020 system, however, was similar to the other systems for the y- and z-directions.

Figure 2 Precision, or within-test standard deviation, for each of the camera systems plotted versus distance between the rigid body and the camera system for (a) x-axis (b) y-axis and (c) z-axis

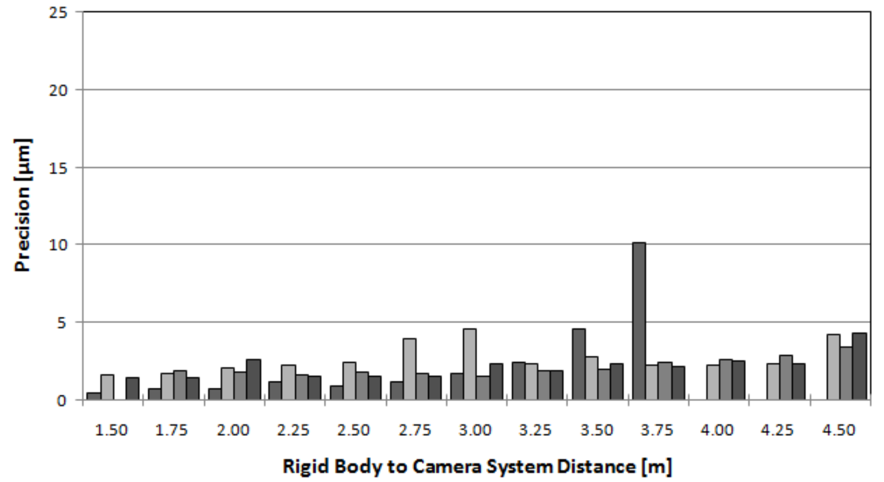


Near-focus	0.6	1.6	0.6	1.1	1.5	1.5	2.2	4.2	6.9	13.7	---	---	---
Mid-focus	8.4	11.6	12.5	9.8	13.4	18.8	10.4	14.1	14.5	20.0	20.2	19.9	9.2
Far-focus	---	3.1	3.4	3.3	3.9	4.6	4.2	4.7	4.9	5.7	5.7	6.7	6.9
Certus	0.8	1.0	1.5	1.3	1.4	1.9	4.1	3.0	3.3	3.7	4.7	5.1	4.4

(a)

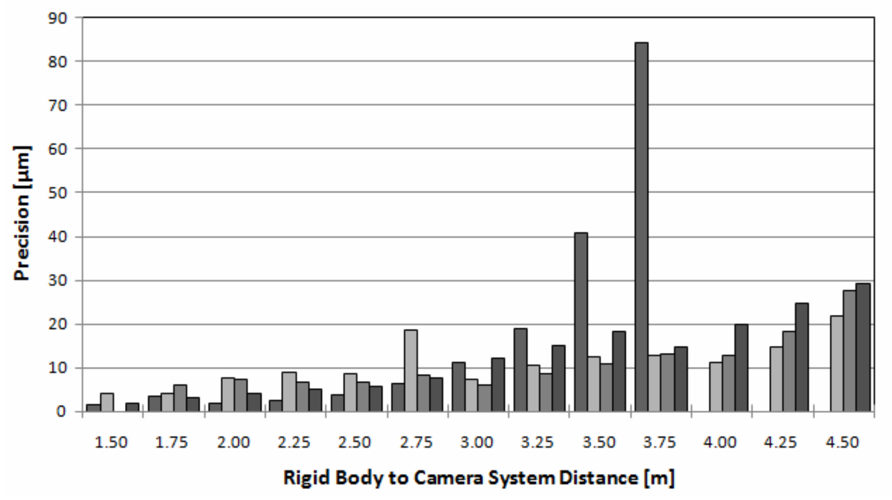
Note: Different scale for the z-axis precision.

Figure 2 Precision, or within-test standard deviation, for each of the camera systems plotted versus distance between the rigid body and the camera system for (a) x-axis (b) y-axis and (c) z-axis (continued)



Near-focus	0.4	0.7	0.7	1.2	0.9	1.1	1.7	2.5	4.6	10.2	---	---	---
Mid-focus	1.6	1.7	2.0	2.3	2.4	3.9	4.6	2.3	2.8	2.3	2.2	2.3	4.3
Far-focus	---	1.9	1.8	1.6	1.8	1.7	1.5	1.9	2.0	2.4	2.6	2.8	3.4
Certus	1.4	1.4	2.6	1.5	1.5	1.5	2.4	1.9	2.3	2.1	2.5	2.3	4.3

(b)



Near-focus	1.5	3.6	2.0	2.7	3.8	6.6	11.2	19.0	40.9	84.2	---	---	---
Mid-focus	4.2	4.2	7.7	8.9	8.6	18.6	7.3	10.6	12.6	12.8	11.3	14.9	21.7
Far-focus	---	6.2	7.5	6.7	6.7	8.5	6.0	8.7	11.0	13.2	13.0	18.2	27.6
Certus	2.1	3.1	4.2	5.2	5.8	7.7	12.1	15.0	18.2	14.8	19.8	24.6	29.2

(c)

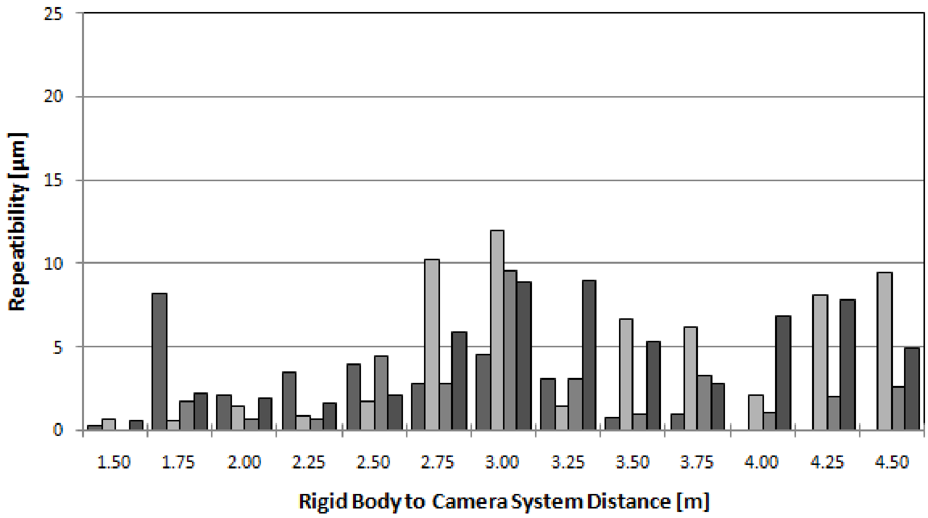
Note: Different scale for the z-axis precision.

Consistent for all directional components of the precision and all camera systems, Figure 2 shows the precision of the marker position tended to decrease with increasing distance between the camera system and the rigid body. Of particular note is the considerable decrease in the z-axis precision of the near focus 3020 system for camera system-to-rigid body distances greater than 3.0 m. For this system, the standard deviation of the location measurements increased from 11.2 to 84.2 μm for the 3.0 and 3.75 m distances, respectively.

Comparison of the two far-focus camera systems showed consistently improved precision in the x-direction and comparable results for the y-direction. The z-direction had improved precision when the camera system was close to the rigid body and slightly decreased precision when the camera system was located farther from the rigid body.

With the exception of the x-direction middle-focus camera system, the in-plane motion (x- and y- directions) generally reported a precision less than 5 μm. The out-of-plane precision was less than 30 μm, with the additional exception of the farther distances of the near focus camera system.

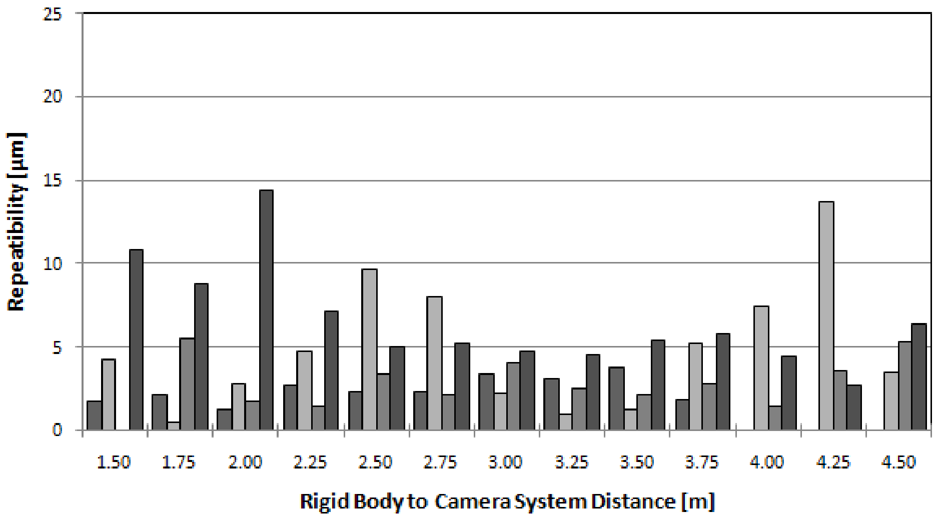
Figure 3 Repeatibility, or between-test standard deviation, for each of the camera systems plotted versus distance between the rigid body and the camera system for (a) x-axis (b) y-axis and (c) z-axis



Near-focus	0.3	8.2	2.2	3.5	4.0	2.8	4.5	3.1	0.7	1.0	---	---	---
Mid-focus	0.6	0.5	1.5	0.8	1.8	10.2	12.0	1.4	6.6	6.2	2.1	8.2	9.5
Far-focus	---	1.8	0.6	0.7	4.4	2.8	9.5	3.1	0.9	3.3	1.1	2.0	2.6
Certus	0.6	2.2	2.0	1.6	2.1	5.9	8.9	9.0	5.3	2.8	6.8	7.8	5.0

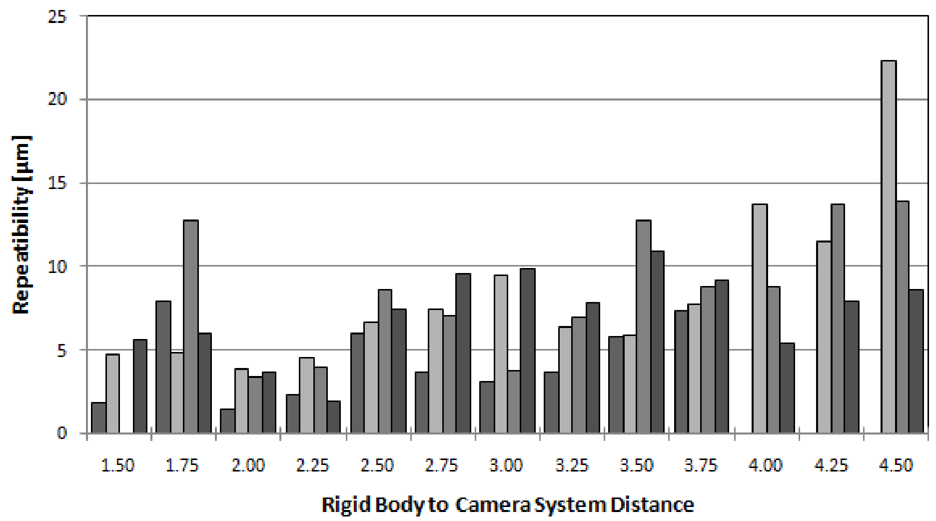
(a)

Figure 3 Repeatibility, or between-test standard deviation, for each of the camera systems plotted versus distance between the rigid body and the camera system for (a) x-axis (b) y-axis and (c) z-axis (continued)



	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50
Near-focus	1.7	2.2	1.3	2.7	2.3	2.4	3.4	3.1	3.7	1.9	---	---	---
Mid-focus	4.3	0.5	2.8	4.7	9.7	8.0	2.2	1.0	1.2	5.2	7.5	13.7	3.5
Far-focus	---	5.5	1.7	1.5	3.4	2.1	4.0	2.5	2.2	2.8	1.5	3.6	5.3
Certus	10.8	8.8	14.4	7.2	5.0	5.2	4.7	4.5	5.4	5.8	4.4	2.7	6.4

(b)



	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50
Near-focus	1.8	8.0	1.4	2.3	6.0	3.7	3.1	3.7	5.8	7.3	---	---	---
Mid-focus	4.8	4.8	3.9	4.5	6.6	7.4	9.4	6.4	5.9	7.8	13.7	11.5	22.3
Far-focus	---	12.8	3.4	3.9	8.6	7.1	3.8	6.9	12.7	8.8	8.7	13.7	13.9
Certus	5.6	6.0	3.7	1.9	7.4	9.5	9.8	7.8	10.9	9.2	5.4	7.9	8.6

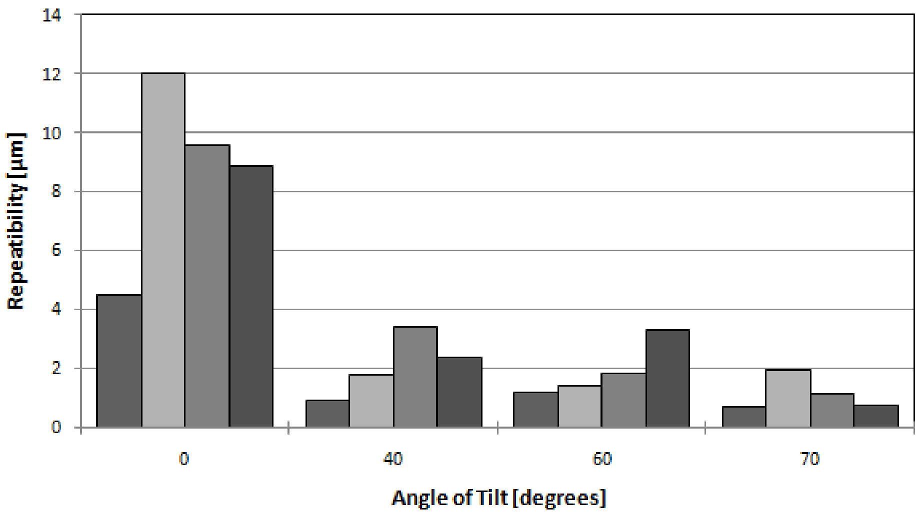
(c)

3.2 Repeatability

The repeatability, or between-trial standard deviation, of the average position for the three directions with the rigid body aligned with the plane of the camera system is reported in Figure 3. In general, the repeatability was consistently under 15 µm for all directions and all camera systems, except for the z-direction repeatability (22.3 µm) of the middle-focus camera system at the farthest camera system-to-rigid body distance of 4.5 m. The repeatability of each of the camera systems is dependent on the distance between the camera system and the rigid body, although no consistent patterns exist. Figure 3(a) shows the x-direction of the in-plane repeatability was slightly diminished when the distance between the camera systems and the rigid body was approximately 3.0m, for all camera systems.

Results from tilting the rigid body away from the plane of the camera system are reported in Figure 4. The in-plane (x- and y- direction) repeatability generally improved with increasing angle, while the out-of-plane repeatability displayed less dependence on the marker angle.

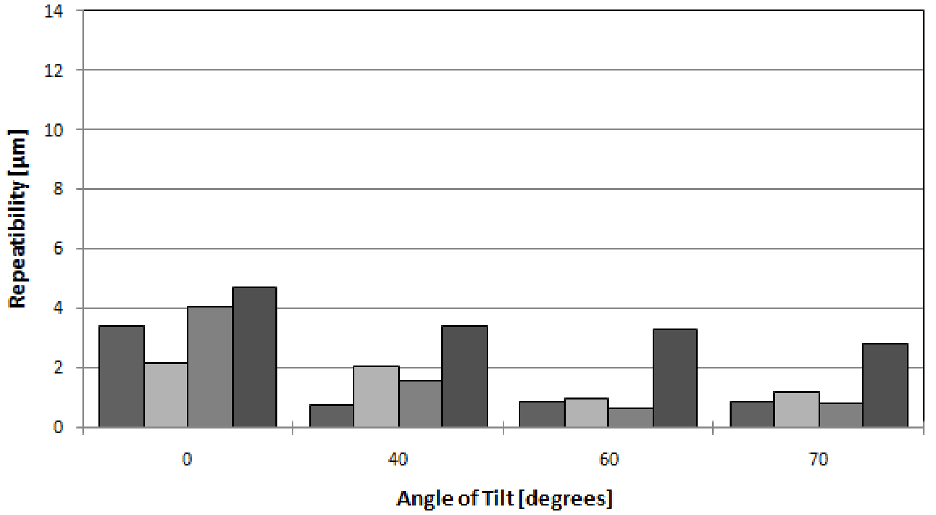
Figure 4 Repeatability, or within-test standard deviation, for each of the camera systems plotted versus angle of tilt of rigid body out of the plane of the camera system for (a) x-axis (b) y-axis and (c) z-axis



	0	40	60	70
3020 Near-focus	4.5	0.9	1.2	0.7
3020 Middle-focus	12.0	1.8	1.4	2.0
3020 Far-focus	9.5	3.4	1.8	1.2
Certus Far-focus	8.9	2.4	3.3	0.7

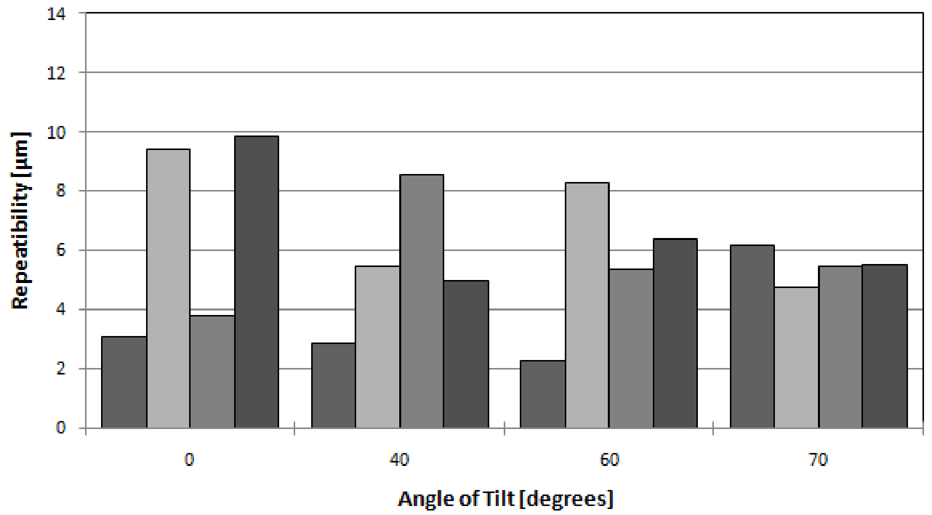
(a)

Figure 4 Repeatability, or within-test standard deviation, for each of the camera systems plotted versus angle of tilt of rigid body out of the plane of the camera system for (a) x-axis (b) y-axis and (c) z-axis (continued)



	0	40	60	70
3020 Near-focus	3.4	0.8	0.9	0.9
3020 Middle-focus	2.2	2.0	1.0	1.2
3020 Far-focus	4.0	1.6	0.7	0.8
Certus Far-focus	4.7	3.4	3.3	2.8

(b)



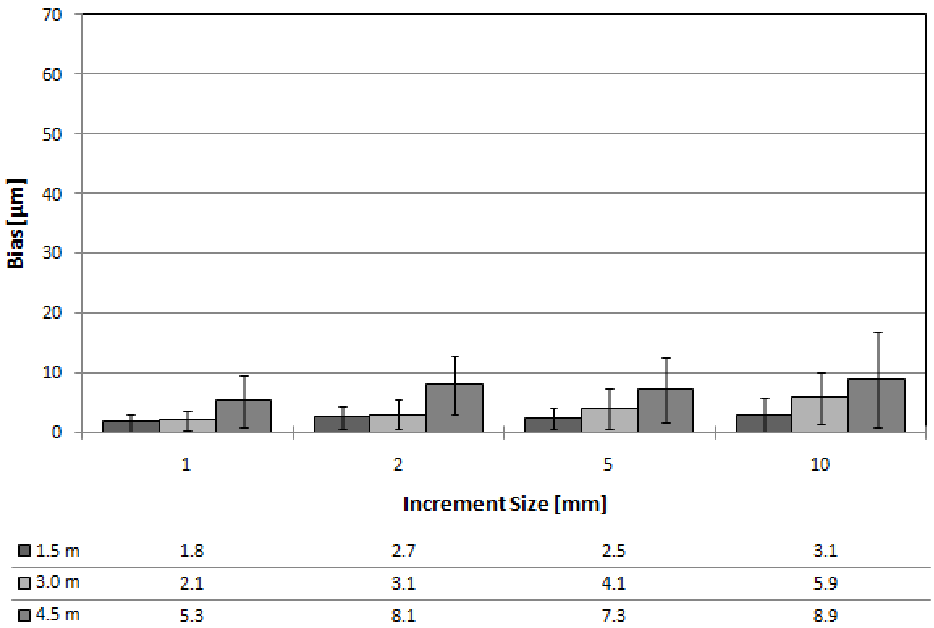
	0	40	60	70
3020 Near-focus	3.1	2.9	2.2	6.2
3020 Middle-focus	9.4	5.5	8.3	4.8
3020 Far-focus	3.8	8.5	5.3	5.5
Certus Far-focus	9.8	5.0	6.4	5.5

(c)

3.3 Accuracy

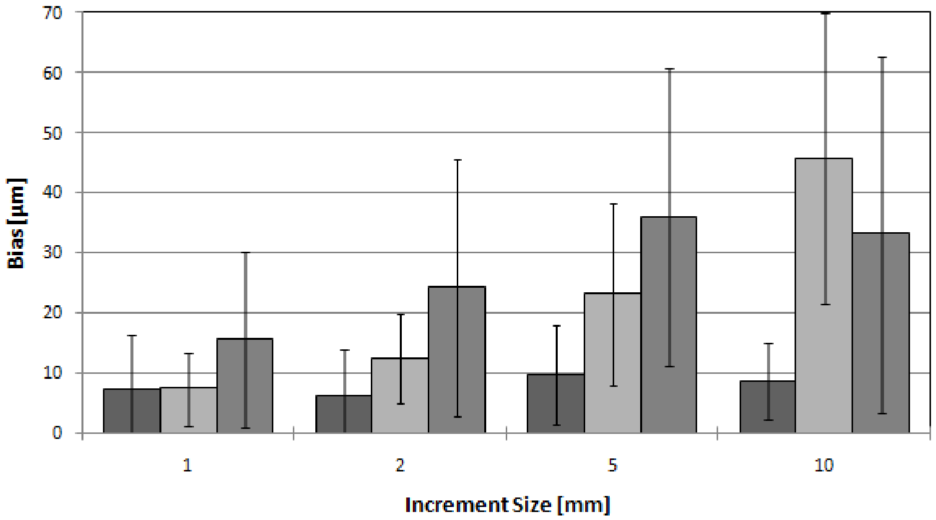
The evaluation of the accuracy of the Optotrak® 3020 system with the middle focal-length configuration is shown in Figure 5. The accuracy is reported in terms of the bias, or the difference between the expected and measured displacement. The accuracy was shown to decrease with increasing distance between the camera system and the rigid body, with the only exception being the 10 mm step size of the out-of-plane motion. The in-plane motion was more accurate than the out-of-plane. The accuracy, independent of the distance or the step size, was always less than 10 µm and 50 µm for the in-plane and out-of-plane motion, respectively. A majority of the in-plane accuracy was less than or close to the resolution of the linear stage. The accuracy was less than 0.53% of the total displacement for the in-plane motion and less than 1.56% of the total displacement for the out-of-plane motion.

Figure 5 Bias, or accuracy, of testing results for the 3020 middle-focus camera system plotted versus distance between rigid body and camera system for (a) y-axis, or in-plane, motion and (b) z-axis, or out-of-plane, motion



(a)

Figure 5 Bias, or accuracy, of testing results for the 3020 middle-focus camera system plotted versus distance between rigid body and camera system for (a) y-axis, or in-plane, motion and (b) z-axis, or out-of-plane, motion (continued)



	1	2	5	10
1.5 m	7.2	6.3	9.7	8.8
3.0 m	7.4	12.4	23.1	45.8
4.5 m	15.6	24.3	36.0	33.1

(b)

4 Discussions

Overall the four Optotrak® camera systems reported good precision, repeatability and accuracy within the suggested operating distances recommended by the manufacturer.

The imprecision found in the x-directional position of the 3020 middle-focus system, can be explained by differences in testing conditions. Specifically, the testing for this camera system was performed on the third floor, while all other camera systems were tested on the ground floor. The x-direction aligns with the height of the building and could be explained by building vibration. Therefore, when performing micron-level testing it is suggested to evaluate the environmental vibrations when choosing a location for testing.

The significant decrease in precision of the near-focus system, as the camera system to rigid body distance increased, was expected due to the system being designed for short range marker tracking. Yet, similar results were not seen for the far-focus camera systems. Therefore, far-focus camera systems may be appropriate for use in close-range experiments, in addition to long-range experiments.

The current study reported precision ranging from 0.6 to 29.2 µm, within the manufacturer's recommended operating range. These results suggest a better precision than previously published. Maletsky et al. (2007) reported precisions less than 100 µm and States and Pappas (2006) reported precision to range from 4.7 to 680 µm. The repeatability reported by States and Pappas was similar to the results of the current study.

The out-of-plane accuracy for the 3020 middle-focus camera system ranged from 6.3 to 45.8 µm, which was similar to the range from 15 to 41 µm previously reported by Maletsky et al. (2007). Although, the current study found better accuracy for in-plane motion between 1.8 and 8.9 µm, as compared to 27 to 47 µm reported by Malestsky et al. (2007). It is noted, for the small bias found for the current study it is difficult to distinguish between error in the measurement system and error in the linear stage, which has a resolution of 5 µm.

Overall the good precision, repeatability and accuracy for the four camera systems studied suggest appropriate use for studies requiring measurement of micron-level motion. An accuracy less than 50 µm and precision less than 30 µm allows for studies of implant stability, in which a threshold of 150 µm is often of interest (Bragdon et al., 1996).

5 Conclusions

All Optotrak® camera systems tested in the current study produced precision, repeatability and accuracy appropriate for use in large- and small- scale studies. One limiting factor for the near-focus camera system would be the measurement volume, since there is a significant decrease in precision when operated outside the recommended 3.0 m range. In addition, all Optotrak® systems would be appropriate for use in micron-level experiments, although additional considerations should be taken to ensure the best possible results. Specifically, the test location should be tested for environmental vibrations. In addition, since the best precision, repeatability and accuracy was found in the x-y plane, it is recommended experiments be performed with the motion of primary interest in the plane of the camera system. A final recommendation when performing micron-level experiments is to have the smallest possible measurement volume. This is achieved by having the experimental setup as close to the camera system as possible, within the manufacturer's recommended range.

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