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Static and dynamic validation of inertial measurement units

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ABSTRACT

Optical motion capture systems are used to assess human motion. While these systems provide a reliable analysis, they limit collection to a laboratory based setting. Devices such as Inertial Measurement Units (IMUs) have been developed as alternative tools. Commercially available IMUs are utilized for a variety of applications; however limited work has been done to determine the reliability of these devices. The objective of this study was to assess the accuracy and precision of a commercially available IMU, containing tri-axial accelerometers, gyroscopes, and magnetometers, under controlled static and dynamic conditions. The sensor output was validated against the gold standard measures of custom made mechanical testing apparatuses. The IMUs provide an accurate (within 0.6°) and precise (within 0.1°) measurement of static sensor orientation and an accurate (within 4.4° per second) and precise (within 0.2° per second) representation of angular velocity. The sensors are more accurate at lower velocities, but the percent error remains relatively constant across all angular velocities. Inclusion of IMUs as an appropriate measurement tool should be based on the application, specific demands and necessary reliability.

1. Introduction

Optical motion capture systems are commonly used to assess human motion. While these systems provide a reliable analysis, they are costly and limit collection to a laboratory based setting. Technological advancements have led to the development of wearable devices such as Inertial Measurement Units (IMUs) as alternative tools to study human kinematics. [1] Advantages of these innovative devices include portability, allowing them to be used outside of a laboratory setting. Commercially available IMUs are being utilized for a variety of applications. The majority aim to identify movement disorders and assess surgical outcomes [2].

Despite their increasing prevalence in both clinical and research applications in recent years, there has been limited work done to identify IMU capabilities and limitations. The majority of publications that include IMU validation compare IMU performance to that of optical motion capture systems. [1,3,4] Optical motion capture systems are considered the gold standard for studying human movement. However, these systems can vary in equipment type, number of cameras, configuration, and biomechanical models, which all may affect measurement accuracy. Mechanical testing has shown that reliable and accurate data can be collected, with error less than 2 mm and 1 ° marker separation, across laboratories [5]. Even with submillimeter manufacturer reported accuracy [3,4], using a system with inherent error as the gold standard limits the validity of the analysis.

The objective of this study was to establish accuracy and precision metrics for a commercially available IMU under controlled conditions. The sensor output was validated against the gold standard measures of custom made mechanical testing apparatuses rather than an optical system. This validation provides performance assessment of the IMU capabilities independent of external system error. A clear understanding of the IMUs strengths and weaknesses will help guide clinical and research applications.

2. Methods

Commercially available Inertial Measurement Units were used for this validation study (Opal version 2, APDM Inc., Portland, Oregon). These IMUs contain tri-axial accelerometers, gyroscopes, and magnetometers. Validation testing was done to establish the accuracy and precision of the IMUs in controlled static and dynamic conditions. For all tests, the following sensor settings were kept constant: synchronized logging recording mode, 128 Hz sample rate, 6 g accelerometer range, and tri-axial components (accelerometer, gyroscope, and magnetometer) enabled. The static testing assessed the sensor's ability to measure orientation data for both small (0–15°) and large (0–180°) angular displacements over short time periods. The marks on the custom made testing apparatuses were used as the gold standard comparison for the sensor output. Dynamic testing assessed the sensor's ability to obtain angular velocity measures for the manufacturer's

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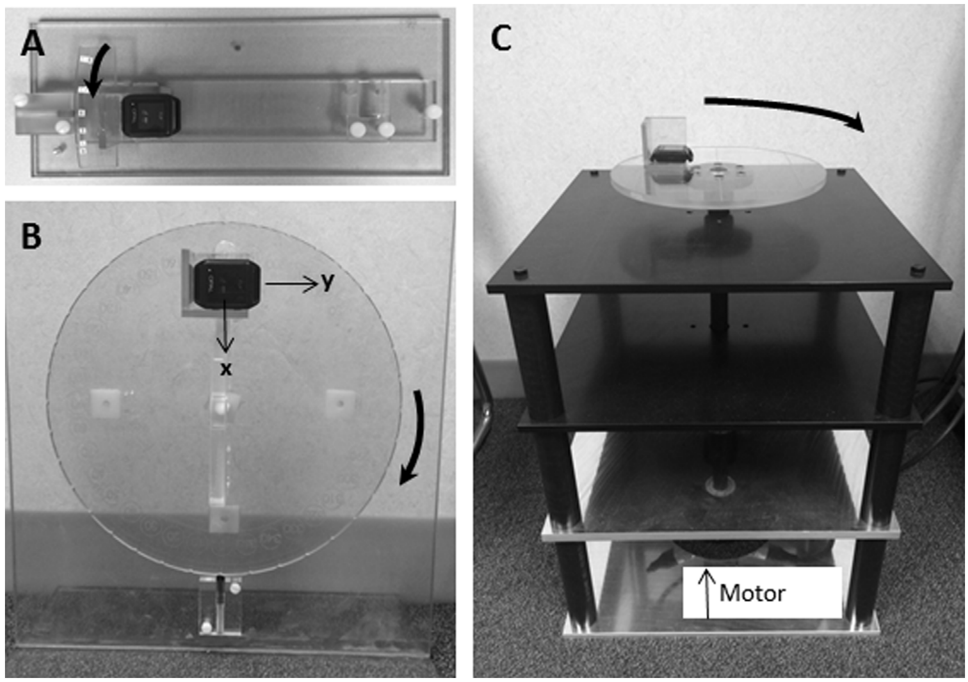

Fig. 1. (A) Small static angle (B) large static angle and (C) dynamic wheel testing apparatus. The sensor is in the position representing rotation about the Z-axis, the sensor coordinate system is shown on Fig. 1B with the Z-axis directed out of the page.

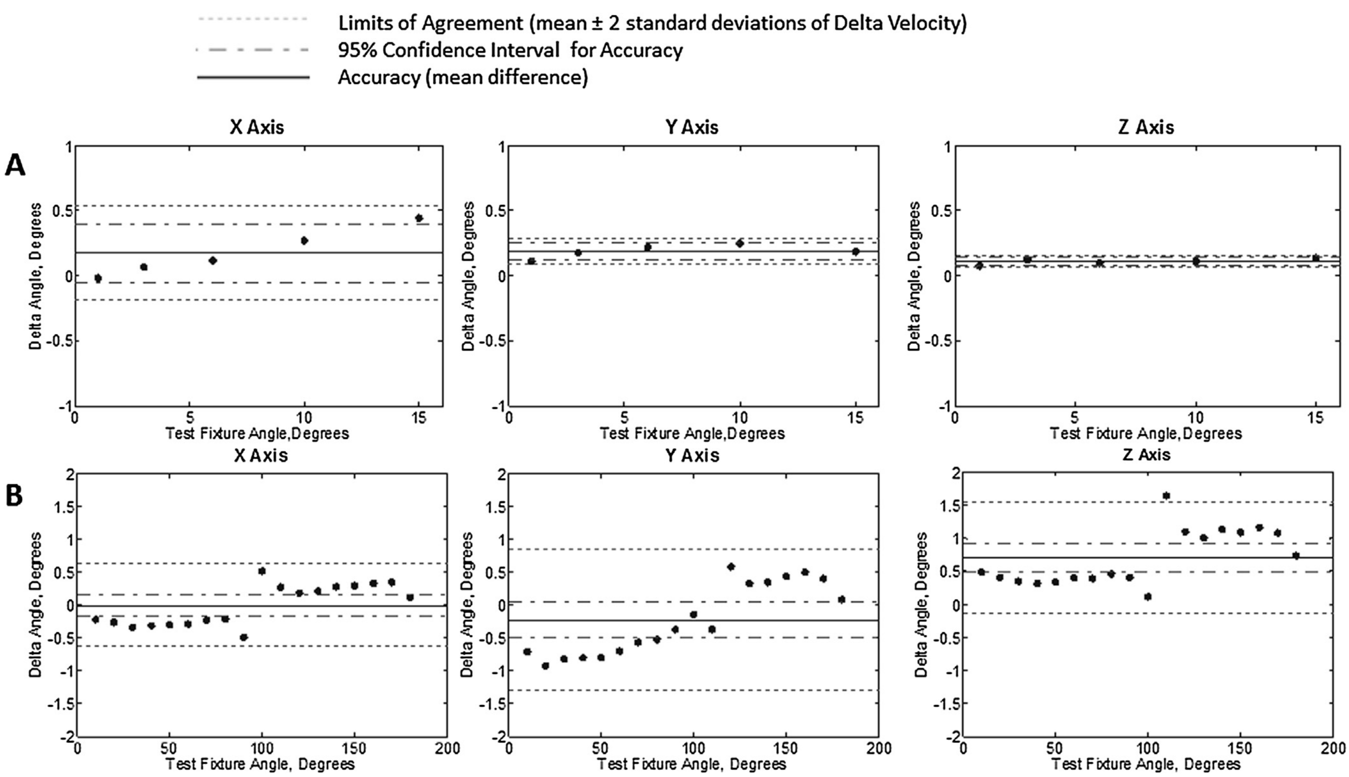

Fig. 2. Representative Bland-Altman plots for a single (A) small angle static and (B) large angle static orientation trial for sensor 4. Delta Angle on the y-axis represents the test fixture angle minus the IMU angle in degrees. The average difference between the fixture angle and the IMU output is within 0.2 ° for the small angle and 0.8 ° for the large angle.

specified range. The angular velocity of a custom made dynamic testing device was compared to the sensor output.

2.1. Static testing

The small angle testing apparatus (Fig. 1A) was used to establish the sensors' performance during small angular displacements at set increments from 0 to 15°. The testing apparatus consisted of a movable arm utilizing a spring-loaded post to lock the arm into notches on a fixed base. The sensor was attached to a custom made mounting device with three orthogonal sides positioned on the arm of the apparatus. The testing apparatus was placed flat on the table so the plane of rotation was perpendicular to the gravity vector and parallel with the ground. The sensor was rotated from 0 to 15 ° where it remained at each notch

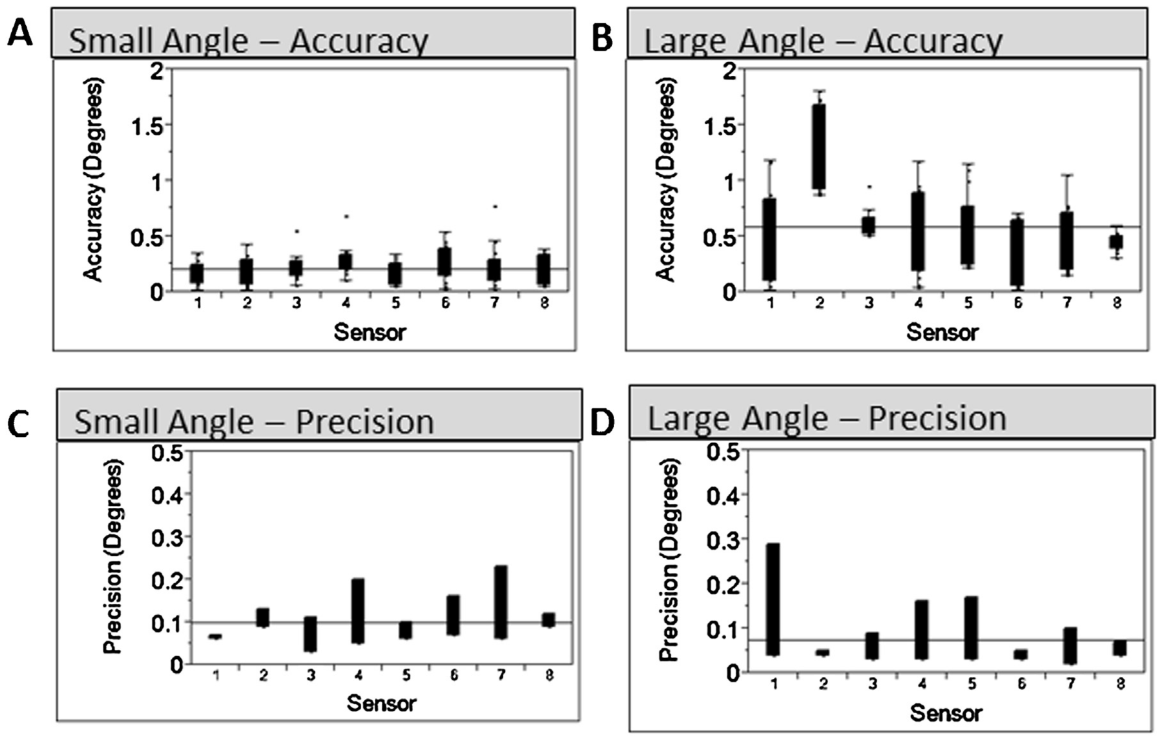

Fig. 3. Box plots of (A) small angle static displacement accuracy, (B) large angle static displacement accuracy, (C) small angle static displacement precision, and (D) large angle static displacement precision. The central line represents the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to ± 1.5 of the interquartile range. The IMUs are accurate to within 0.6 ° and have precision within 0.1 ° of static sensor orientation.

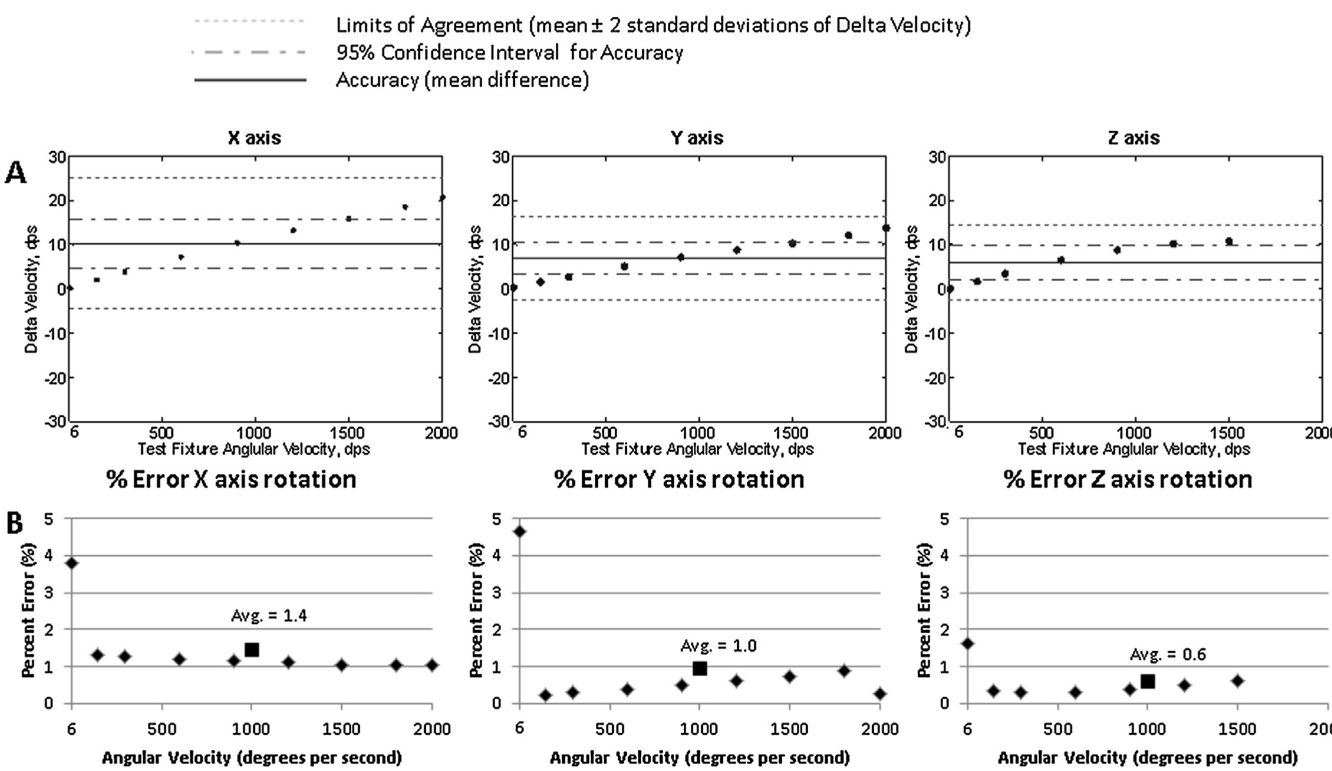

Fig. 4. Representative (A) Bland-Altman and (B) percent error plots for a single dynamic angular velocity trial for sensor 4. Delta Velocity on the y-axis of the Bland-Altman plot represents the testing device angular velocity minus the IMU output in degrees per second (dps), the average difference is within 10.0 dps. On the percent error plots, the average accuracy for all velocities is represented by the black square, 1.4% for the X-axis, 1.0% for the Y-axis, and 0.6% for the Z-axis.

(0, 1, 3, 6, 10, and 15°) for 10 s (total trial time approximately 1 min). This protocol was repeated five times for each of the three different sensor positions (fifteen trials per sensor). The three sensor positions represented rotation about each of the sensors' three axes. These fifteen trials were repeated for eight Opal sensors (120 total small angle trials).

The large angle testing apparatus (Fig. 1B) consisted of a rotating wheel with a spring-loaded post mechanism with notches at every 10 ° increment from 0 to 360°. The large angle displacement test followed a

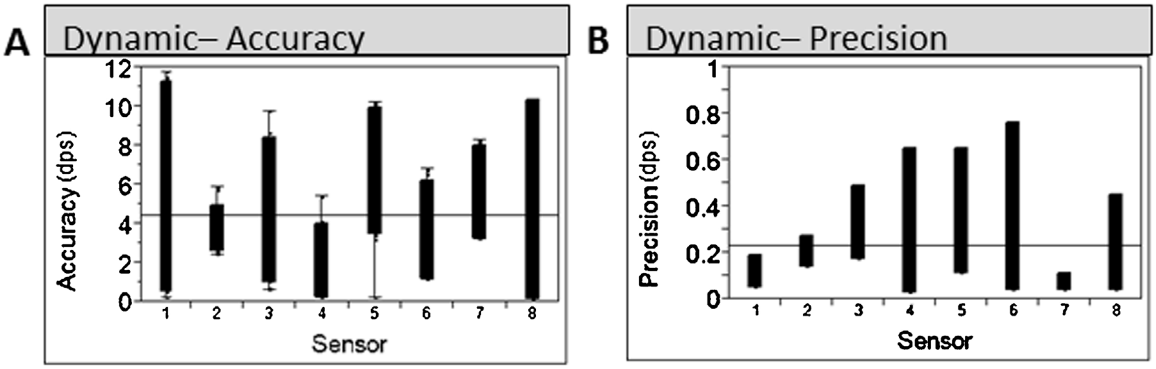

Fig. 5. Box plots of (A) accuracy and (B) precision of dynamic validation tests. The central line represents the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to ± 1.5 of the interquartile range. The IMUs are accurate to within 4.4 ° and have precision to 0.2 ° per second (dps) for speeds up to 2000 dps.

similar protocol as the small angle. The same custom mounting jig was attached to the wheel apparatus. The wheel apparatus was placed with the plane of rotation parallel to the gravity vector and perpendicular to the floor. The sensor was rotated from 0 to 180 ° in 10 ° increments for 10 s (trial time approximately 3 min). Each sensor was tested at each position five times for a total of 120 large angle trials.

For each trial, small and large angle, the sensor orientation output for the axis of rotation for the middle five seconds for each position, an average of approximately 640 data points, was compared to the angle denoted on the test fixture. The other two axes orientation data were compared to zero as there was no rotation in those planes. Each individual sensor's magnetometer was recalibrated prior to initial testing and between sensor positions (every 5 trials) to ensure that the prior testing did not impact the results and that each sensor was evaluated in the best scenario possible. For research studies and use in the clinic it is not necessary to recalibrate the sensors this frequently. The manufacturer provides guidelines for certain scenarios where recalibration is necessary. In related testing the researchers saw no evidence to warrant recalibration of sensors when kept in the same area as the previous recalibration. Both static testing apparatuses' notches were within ± 0.02 ° of the specified angle per the milling machine's specifications [6].

2.2. Dynamic testing

The dynamic testing device (Fig. 1C) was used to establish the sensors' angular velocity performance. The custom made device was powered by an AKM series Servo Motor (Kollmorgen; Radford, VA) with a Micron Precision Gearhead with 10:1 reduction (Thomson; Radford, VA). The motor rotated a 26 cm diameter acrylic disc positioned on a delrin and aluminum base with ceramic bearings. APDM technical specifications report the X- and Y- axis gyroscopes with a range of ± 2000 ° per second (dps) and the Z-axis gyroscope with a range of ± 1500 dps. For testing, the angular velocity inputs for rotation about the X-and Y-axes were: 6, 150, 300, 600, 900, 1200, 1500, 1800, and 2000 dps. The inputs for rotation about the Z-axis were: 6, 150, 300, 600, 900, 1200, and 1500 dps. The same eight sensors used for static testing were included in the dynamic testing. Each sensor was recalibrated prior to beginning testing and between switching axis of rotation (every 5 trials). The order of input velocities was randomly generated for each sensor. Each of the eight sensors underwent five trials in each of the three positions (rotation about x-, y-, and z-axes) for a total of 120 dynamic trials. A trial consisted of the sensor being rotated at the above velocities for 10 s for a total trial time of approximately 90 s for rotation about x-and y-axes and approximately 70 s for rotation about the z-axis. The sensors were not rotated about their center of masses. For each trial, the sensor output angular velocity for the axis of rotation was compared to the input velocity of the dynamic testing device. The testing device output (motor and gearhead) was rated to 0.003 ° per second.

2.3. Data analysis

For static orientation assessments, the sensor output orientation quaternion was transformed to Cardan angles. The APDM algorithm produces an orientation quaternion output from the tri-axial data:

Orientation quaternion (q) = $[q_0\ q_1\ q_2\ q_3]$

The quaternion (q) was first converted into the direction cosine matrix (R) [7]:

$$\text{Direction cosine Matrix (R)} = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1q_2 - q_0q_3) & 2(q_{01}q_2 + q_1q_3) \\ 2(q_1q_2 + q_0q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_0q_1 + q_2q_3) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}$$

A static position was selected and the direction cosine matrix was transformed in relation to this static position. The various Cardan angle transformations were then analyzed to generate the three rotation angles given the associated order of rotation. Once Cardan angles were obtained, they were compared to testing device known angle measures.

To evaluate both static and dynamic sensor performance, accuracy and precision were assessed for the axis of rotation at the mid-point of each test interval. The Bland Altman method [8] was used to assess the agreement between the test apparatus value and the sensor output. Accuracy is reported as the absolute value of the difference between the gold standard of the test apparatus and the sensor output value. Precision was calculated using the standard deviation (σ) of each measurement point (angle or degrees per second) between trials,

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

where $\bar{x}$ is the mean. The difference (accuracy) and standard deviation (precision) were averaged across trials for each sensor at each position and averaged for the eight sensors across all positions. Both were calculated using custom software (MATLABR2013b, The MathWorks Inc., Natick, MA, 2000). To evaluate the influence of angular velocity on the error, percent error was calculated for the dynamic trials,

$$\%\text{error} = \left(\frac{|\text{measured} - \text{accepted}|}{\text{accepted}}\right) \times 100.$$

where the accepted value is the velocity input into the dynamic testing device and the measured value is the IMU output.

3. Results

3.1. Static validation test

The small angle measurement error does not appear to be systematic as the difference between the test fixture value and sensor output angle do not have a notable relationship (Fig. 2A). The large angle displacement error does appear to have a somewhat sinusoidal appearing relationship (Fig. 2B). The measurement errors were smaller for the small angle testing than the large angle testing. All sensors produced a larger error around the 90 ° point. While this point appears to be related to a trigonometric calculation incongruity, the error is within the two standard deviations band.

For both the large and small angular displacement testing, the average sensor output accuracy (Fig. 3A) was within 0.6 ± 0.1 ° of the test fixture value. The sensors were more accurate on the small angle testing apparatus with an average accuracy within 0.2 ± 0.1 ° of the fixture value versus within 0.6 ± 0.1 ° on the large angle testing apparatus. The sensors had equal precision on the large and small angle testing apparatuses (Fig. 3C & D) with average precision of 0.1 ± 0.1°.

3.2. Dynamic validation test

Representative Bland-Altman plots for a single trial of one of the sensors in each of the three positions are shown in Fig. 4A. A systematic error is apparent, an increase in angular velocity results in an increase in the difference between the testing device input and IMU output. The average error for a dynamic trial of a sensor is less than 1.5 dps (Fig. 4B). The dynamic testing average accuracy for all eight sensors was 4.4 ± 0.2 dps (Fig. 5A) and precision was 0.2 ± 0.3 dps (Fig. 5B). The highest error occurred during the accuracy testing of sensor 1. The testing went up to speeds of 2000 dps. This translates to an error of 0.6% based on full scale output. The highest error occurred when rotation was around the x-axis, consistent with the static orientation error.

4. Discussion

This study demonstrated that a commercially available IMU has excellent utility and reliability. In the controlled static testing conditions, the IMUs showed exceptional accuracy and precision, average accuracy and precision was within ± 1.0°. This is superior to the manufacturer's reported static orientation accuracy estimates of 1.15 ° (roll/pitch) and 1.50 ° (heading) (www.apdm.com). These results have slightly lower accuracy and higher precision than the study by Lebel et al. comparing APDM Opal to Optotrak motion capture orientation at static positions (accuracy 0.01° ± 2.9°) [3], but they are similar to results obtained using motion capture. The large angle trials had higher differences between the testing device and IMU outputs than the small angle trials. This is something to take into consideration when evaluating what range of motion will be assessed. There is no notable discrepancy in performance between axes, with average values for the three axes precision within 0.1 ° and accuracy within 0.2 ° of one another.

In the controlled dynamic conditions, the IMUs showed good angular velocity accuracy and precision. The linear systematic error in the Bland-Altman plots show that the sensors are more accurate at lower angular velocities, but the percent errors for the higher velocities were not markedly greater. Maximum angular velocities of 2000 dps are reached by elite pitchers shoulder joint and sprinters knee joint. [9,10] Activities of daily living in the general population are far from this maximum velocity. During sit to stand movement, maximum angular velocities for hip and knee extension are less than 200 ° per second. [11] During stair descent, maximum knee angular velocity is approximately 210 ° per second [12]. When considering utilizing IMUs for data collection, the expected velocities of the application are important to consider when predicting accuracy.

Limitations for this study include that these validation results are limited to an isolated controlled setting. Multiplane motion and long duration scenarios were not assessed. All tests were planar tests. Given the lack of motion in the third dimension, the off axis rotation reliability was not reported. Future studies could be designed and performed to assess the 3D rotation reliability.

5. Conclusion

The IMUs provide an accurate (within 0.6°) and precise (within 0.1°) measurement of static sensor orientation. Accuracy is improved on smaller rather than larger displacements. The IMUs provide an accurate (within 4.4 ° per second) and precise (within 0.2 ° per second) representation of angular velocity. The sensors are more accurate at lower velocities, but percent error remains relatively constant across angular velocities. When determining whether IMUs are the appropriate tool, it is important to consider the application specific demands and necessary reliability.

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