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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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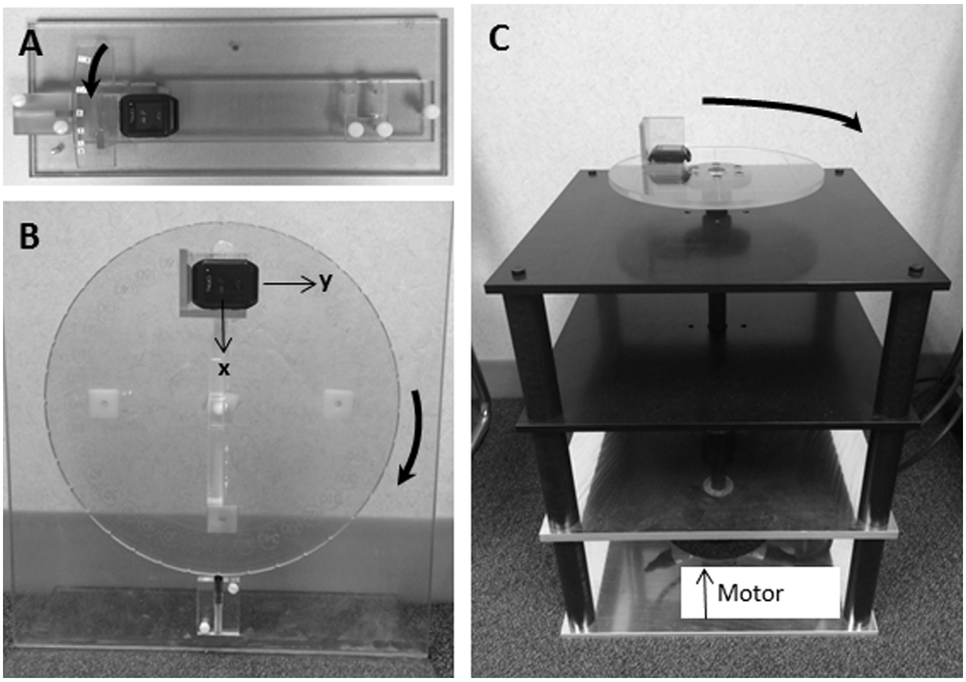

Fig. 1. (A) Small static angle (B) large static angle and (C) dynamic wheel testing apparatus. The sensor is in the position representing rotation about the Z-axis, the sensor coordinate system is shown on Fig. 1B with the Z-axis directed out of the page.

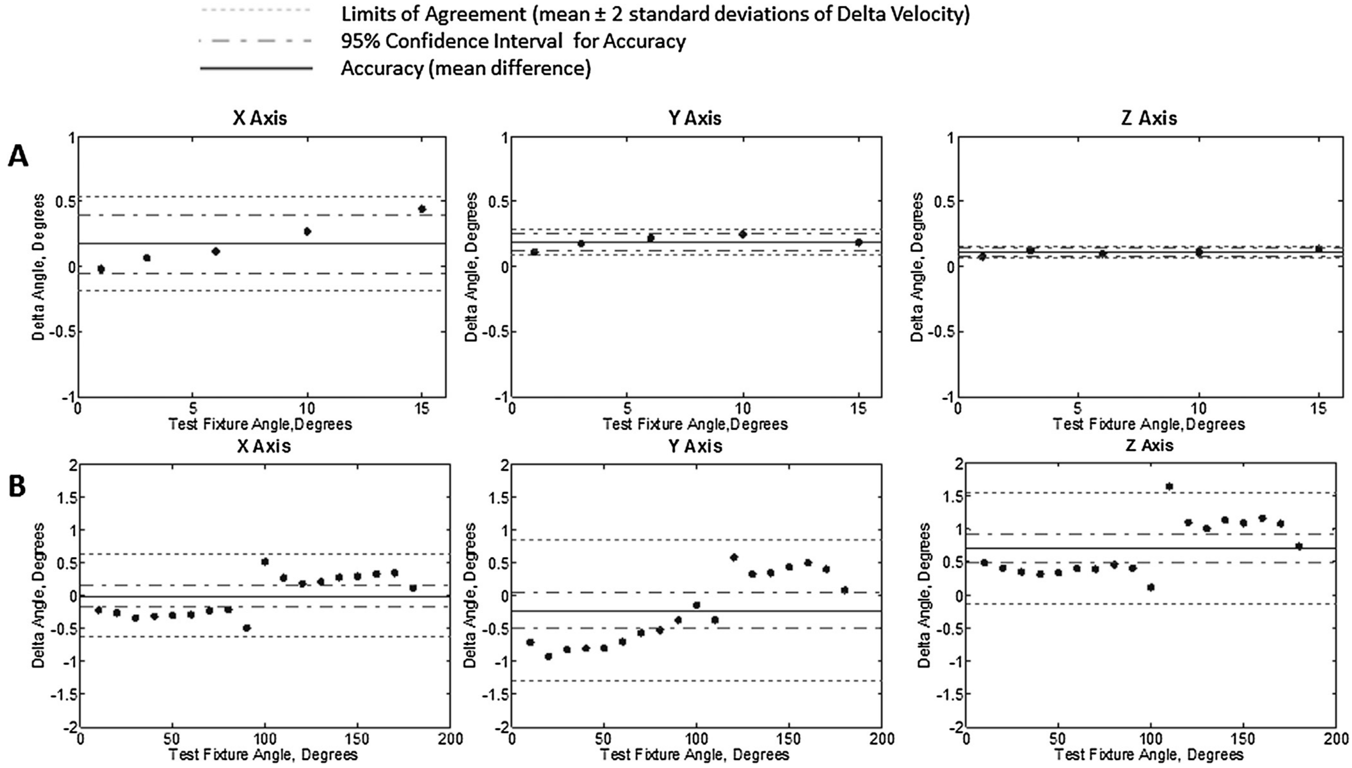

Fig. 2. Representative Bland-Altman plots for a single (A) small angle static and (B) large angle static orientation trial for sensor 4. Delta Angle on the y-axis represents the test fixture angle minus the IMU angle in degrees. The average difference between the fixture angle and the IMU output is within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