Reliability and validation of an inertial sensor used to measure orientation angle

Conference Paper · July 2016

5 authors, including:

Benjamin K Williams
Aspire Academy

Joong Hyun Ryu
Aspire Academy

Pitre C Bourdon
University of South Australia

Peter J Sinclair
The University of Sydney

RELIABILITY AND VALIDATION OF AN INERTIAL SENSOR USED TO MEASURE ORIENTATION ANGLE

Benjamin Kane Williams[1,2], Joong Hyun Ryu[1], Pitre Collier Bourdon[1,3], Philip Graham-Smith[1] and Peter J. Sinclair[2]

Sport Science Department, Aspire Academy, Doha, Qatar[1]
Discipline of Exercise and Sport Science, The University of Sydney, Sydney, Australia[2]
School of Health Sciences, University of South Australia, Adelaide, Australia[3]

This study examined the reliability and validity of an inertial measurement unit (IMU) for measuring orientation angle. An IMU was mounted onto a goniometer and moved through 0-90° with data collected at 10° increments. The process was repeated 10 times for all 3 axes. Reliability was measured via a typical error (TE) analysis from the 10 repeated trials. Validity was determined via a Pearson correlation and an ordinary least products (OLP) regression. The IMU was very reliable for all 3 axes (TE: x=0.03°, y=0.03°, z=0.02°). The Pearson correlation between the IMU and goniometer was large and significant for all 3 axes (r = 1.00, 95%CI = 1.0-1.0). The OLP regression showed no proportional bias for the 3 axes and only small fixed bias for the x and z axes. Overall the IMU tested was very reliably and accurate at measuring orientation angle.

KEY WORDS: validity, error, IMU, accelerometer, accuracy.

INTRODUCTION: Historically, kinematic data has generally been collected via high-speed optical systems that allow for the capture of dynamic movements. However, those systems are restrictive in that they can be expensive, only allow measurements in a limited volume and the data analysis can be time consuming. As such, the use of inertial measurement units (IMUs) are becoming increasingly more prevalent in sports biomechanics research and applied biomechanics servicing (Fasel, Favre, Chardonnens, Gremion, & Aminian, 2015; van der Slikke, Berger, Bregman, Lagerberg, & Veeger, 2015). This is in part due to the lower cost, improved accuracy, and wider availability of IMUs (Aydemir & Saranlı, 2012). There have been numerus studies investigating various aspects of sports biomechanics using IMU's including tennis stroke classification (Connaghan et al., 2011), wheelchair kinematics during wheelchair basketball (van der Slikke et al., 2015) and spatio-temporal parameters during cross country skiing (Fasel et al., 2015).
Like any mechanical sensor device IMU's have associated measurement errors. Depending on the sensors within an IMU (accelerometers, gyroscopes, magnetometers) and the type of data being collected, the error sources can be multiple. Some of the possible errors can include; fixed bias error's or drift; scale factor errors; cross-coupling errors, g-dependent bias errors, and magnetic field errors (Aydemir & Saranlı, 2012). In order to minimise the amount of error within any data collection a careful calibration must be carried out prior to use.
In order for any biomechanical data collection and analysis to be meaningful it must first be reliable and valid. Reliability refers to the reproducibility of a measurement and can be quantified by taking multiple measures on or with the same subject/piece of equipment (Hopkins, 2000). Criterion validity can be established by comparing data to that of a "gold standard" or criterion measure (Currell & Jeukendrup, 2008).
The purpose of this study was to evaluate the reliability and validity of an IMU for measuring orientation angle. This initial study will form part of a larger study that will also evaluate the IMU for measuring other variables with the aim to use it as a method of collecting data on racket kinematics and measuring swing parameters.

METHODS: Equipment set-up: The inertial measurement unit (IMU) used was a 3-Space Wireless 2.4 GHz DSSS unit (YOST Labs, USA). It was a High-G unit capable of measuring

± 24 g. The data from the IMU were transmitted in real-time at 105 Hz to a computer via a 3-Space Wireless Dongle (YOST Labs, USA) connected to a USB port into a computer. The 3-Space Sensor Software Suite program was used to collect all data.

Testing protocol: The IMU was calibrated according to the manufactures instructions within the 3-Space Sensor software in an area away from any metal. It was then fixed to a goniometer (Baseline Evaluation Instruments, USA) resting on a flat wooden surface and moved through a range of 0-90° in a single plane (x). Data were collected at 10° increments through the range (10 data points). This process was repeated 10 times. The IMU was then rotated and refixed onto the goniometer such that the IMU moved through the remaining 2 planes (y and z). Data were collected as above for the remaining planes.

Data analysis: The IMU data were filtered within the 3-Space Sensor software using a Kalman filter for attitude heading reference systems, to compensate for magnetic field distortion (Yadav & Bleakley, 2014). Data from the IMU were then exported to MATLAB (version 8.6, The MathWorks, USA) and converted from radians to degrees. The reliability of the IMU was determined via a typical error (TE) analysis from repeat trials (standard deviation of the differences between trials divided by the square root of 2) in which all 10 trials at a set angle were analysed (Hopkins, 2000). The reliability data were assessed using spreadsheets from Hopkins (Hopkins, 2015). All other data analyses were done using SPSS Statistics software (IBM, version 22). The orientation data from the IMU were compared to the goniometer using both Pearson product-moment correlation coefficients, as well as ordinary least products (OLP) regression (Ludbrook, 2002). Significance was set at $p < 0.05$. Confidence intervals (CI) for the Pearson analysis were determined using the SPSS bootstrapping module (Weaver & Koopman, 2014). Correlation effect sizes were considered as small (± 0.1 - ± 0.29), medium (± 0.3 - ± 0.49) and large (± 0.5 - ± 1.0) (Cohen, 1988).

RESULTS: The mean TE scores from the 10 repeat trials for each orientation are presented in Table 1.The Pearson and OLP analyses for each of the orientations are shown in Table 2.

Table 1
Mean typical error scores and 95% confidence intervals for the 3 orientations of the IMU

	Typical Error (degrees)	95% CI (degrees)
Roll (x)	0.03	0.03-0.04
Pitch (y)	0.03	0.02-0.03
Yaw (z)	0.02	0.02-0.03

Table 2
Correlations between the IMU and goniometer

Orientation	Person r			ordinary least products regression					
	r	95% CI	*P*	a	95% CI (a)	b	95% CI (b)	Proportional bias	Fixed bias
Roll (x)	1.00	1.0-1.0	0.00	-0.17	-0.33--0.01	1.00	0.99-1.00	None	Yes
Pitch (y)	1.00	1.0-1.0	0.00	0.34	-0.26-0.94	1.00	0.99-1.01	None	None
Yaw (z)	1.00	1.0-1.0	0.00	0.38	0.01-0.66	1.00	0.99-1.00	None	Yes

DISCUSSION: The ability of an IMU to reliably and accurately collect data is paramount for its data to be meaningful. The first step to ensuring quality data is the calibration process. While initially piloting this study there were discrepancies and drift errors associated with the measured data from the IMU. After some investigation it was discovered that the calibration

of the IMU and subsequent data collection was close enough to metal (i.e., metal table frame) to affect the magnetometer within the IMU. This study was therefore conducted in an environment away from any metallic interference.
The results of the reliability analyses demonstrated that the IMU tested was extremely reliable at measuring orientation angle in all three planes (Table 1). This research compares favourably with other reliability studies involving IMU's such as Mancini, Chiari, Holmstrom, Salarian, and Horak (2016) who showed that the test-retest reliability of IMU's to measure gait initiation characteristics was moderate to excellent.
The correlation analyses showed a large correlation between the IMU and the goniometer (Table 2). The Pearson r of 1.00 for all three planes demonstrated near perfect correlations. The results in this study are similar to that of Brodie, Walmsley, and Page (2008b) who showed that the maximum absolute static orientation error could be less than 1°, if re-calibrated correctly prior to measurement.
This study used a goniometer as the "gold standard" to measure validity, while other studies have used optical motion analysis systems. van der Slikke et al. (2015) used a 24 camera motion analysis system to validate the use of IMU's to measure wheelchair basketball kinematics. They found that the IMU's were reliable, once they applied an algorithm to correct for the "skidding" of the wheels, with low root mean square error values and high correlations with the motion analysis system.
The results of the OLP regression showed that there was no proportional bias (the IMU measurement doesn't give higher or lower values than the goniometer by an amount proportional to the level of the measured variable). However a very small fixed bias was found in the yaw (x) and roll (z) orientations (Table 2) suggesting a small constant difference in values between measurements. It is possible that with better calibration prior to collecting data these fixed biases could be reduced. Similarly, Clark et al. (2012) showed that a commercial video game system, capable of real-time 3D full-body anatomical landmark positional data, had concurrent validity. They compared it against a 3D motion analysis system and found Pearson r values >0.90 for most measurements. However, there was proportional bias found, as shown by OLP regression analyses, for the pelvis and sternum areas, although the authors believed it would be possible to apply calibration equations to correct for the biases.
Although the static accuracy of the IMU in this study is very high, it could be that the dynamic accuracy is somewhat reduced, similar to that found by Brodie, Walmsley, and Page (2008a). In contrast to their study involving static measurements, they found a much greater error (30° maximum orientation error) when the IMU was moving on a pendulum. However, once they applied a custom fusion algorithm the maximum error between the IMU and motion capture data was reduced to 1.3°.
Overall, based on the results of the reliability, correlation and OLP analyses, the authors believe that the IMU assessed is extremely reliable and possesses criterion validity for measuring static orientation angle. Further studies are currently underway to assess other measureable variables from the IMU (i.e., acceleration, angular velocity), such that the reliability and validity of those measures can be known before utilising the IMU in sports biomechanical studies.

CONCLUSION: The IMU used in this study has been shown to be very reliable and valid when measuring orientation angle compared to a goniometer. The IMU could potentially be used in place of an optical motion analysis system to provide orientation angle data during various sports biomechanical applications. This could overcome some of the restrictions of traditional 3D optical analysis systems and allow meaningful data collection within real-world settings outside the confines of a laboratory.

REFERENCES:

Aydemir, G. A., & Saranlı, A. (2012). Characterization and calibration of MEMS inertial sensors for state and parameter estimation applications. *Measurement, 45*(5), 1210-1225.
Brodie, M. A., Walmsley, A., & Page, W. (2008a). Dynamic accuracy of inertial measurement units during simple pendulum motion. *Computer Methods in Biomechanics and Biomedical Engineering, 11*(3), 235-242.
Brodie, M. A., Walmsley, A., & Page, W. (2008b). The static accuracy and calibration of inertial measurement units for 3D orientation. *Computer Methods in Biomechanics and Biomedical Engineering, 11*(6), 641-648.
Clark, R. A., Pua, Y.-H., Fortin, K., Ritchie, C., Webster, K. E., Denehy, L., & Bryant, A. L. (2012). Validity of the Microsoft Kinect for assessment of postural control. *Gait & Posture, 36*(3), 372-377.
Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Hillsdale, NJ: L. Erlbaum Associates.
Connaghan, D., Kelly, P., O'Connor, N. E., Gaffney, M., Walsh, M., & O'Mathuna, C. (2011). Multi-Sensor Classification of Tennis Strokes. *2011 Ieee Sensors*, 1437-1440.
Currell, K., & Jeukendrup, A. E. (2008). Validity, Reliability and Sensitivity of Measures of Sporting Performance. *Sports medicine, 38*(4), 297-316.
Fasel, B., Favre, J., Chardonnens, J., Gremion, G., & Aminian, K. (2015). An inertial sensor-based system for spatio-temporal analysis in classic cross-country skiing diagonal technique. *Journal of Biomechanics, 48*(12), 3199-3205.
Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports medicine, 30*(1), 1-15.
Hopkins, W. G. (2015). Spreadsheets for analysis of validity and reliability. *Sportscience, 19*(36-42). sportsci.org/2015/ValidRely.htm Retrieved from sportsci.org/2015/ValidRely.htm
Ludbrook, J. (2002). Statistical Techniques For Comparing Measurers And Methods Of Measurement: A Critical Review. *Clinical and Experimental Pharmacology and Physiology, 29*(7), 527-536.
Mancini, M., Chiari, L., Holmstrom, L., Salarian, A., & Horak, F. B. (2016). Validity and reliability of an IMU-based method to detect APAs prior to gait initiation. *Gait & Posture, 43*, 125-131.
van der Slikke, R. M. A., Berger, M. A. M., Bregman, D. J. J., Lagerberg, A. H., & Veeger, H. E. J. (2015). Opportunities for measuring wheelchair kinematics in match settings; reliability of a three inertial sensor configuration. *Journal of Biomechanics, 48*(12), 3398-3405.
Weaver, B., & Koopman, R. (2014). An SPSS macro to compute confidence intervals for Pearson's correlation. *Quantitative Methods for Psychology, 10*(1), 29-39.
Yadav, N., & Bleakley, C. (2014). Accurate Orientation Estimation Using AHRS under Conditions of Magnetic Distortion. *Sensors, 14*(11), 20008-20024.