COMPARISON OF SIMPLE GRAVITY BASED ACCELEROMETER CALIBRATION PROCEDURES

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Accelerometers are commonly used, yet the process of calibrating them and the influence this has on recorded accelerations is rarely reported. The aim of this study was to compare the accuracy of three simple gravity based calibration methods of accelerometers. Using a custom made rig, 16 Delsys Trigno sensors were simultaneously calibrated by positioning the sensors in 9 positions throughout the full range of orientations across three axes. Three calibration methods were used spanning a range of 1g (1G), 2g (2G), and 2g with optimisation (2Gopt). Errors were greatest in 1G (RMSD=3.1%) and equally as good for the 2G and 2Gopt (2.1%). Gravity based calibration of accelerometers can be achieved quickly, and calibration over a larger range provides more accurate results. This work provides recommendations of accelerometer use which help the applied practitioner to collect more reliable and valid data. Further investigation of factors, including those affecting the frequency of calibration, is required.

KEY WORDS: Accuracy, Error, IMU.

INTRODUCTION: The use of accelerometers, whether alone or integrated with other sensors such as Inertial Measurement Units (IMUs), are now commonly used as the technology becomes more readily available and inexpensive. These allow for relatively quick, and efficient data collection for a large number of participants (e.g. Sheerin et al., 2018) and in applied settings (e.g. Zhang et al., 2019). Various technologies are used in their construction, some of which are more prone to deteriorations in accuracy, partially through loss of calibration. Consequently, such devices need to be calibrated at least as frequently as recommend by the manufacturers. Calibration can be affected by factors including frequency and harshness of use, inappropriate use (e.g. being dropped on the ground), and variations in environmental conditions (e.g. temperature). Where the measurement range is small (e.g. <16g), such devices are likely being used more harshly in sports biomechanics, up to and beyond their measurement limits., As such, accelerometers would likely need to be calibrated more frequently (e.g. once or more per testing day). There are a range of methods to calibrate accelerometer devices (see British Standards Institution, 1999). These include laser interferometry, potentially the high-precision gold-standard, mid-range back-to-back comparisons, and more simple gravity based techniques. The frequency and method of calibrating such devices is rarely reported in the literature, and as such limited recommendations exist. On a practical level, the gravity based methods are the most readily available, and as they are simple and inexpensive it might provide sports biomechanists with the opportunity to calibrate more frequently as required. There are a variety of gravity based methods which vary the ranges over which the data is calibrated (e.g. 0g to 1g; -1g to 1g), or more detailed computations used in determining calibration values such as a Newtonian optimisation (e.g. Frosio et al. 2009). The aim of this study was to compare the accuracy of various simple gravity based calibration methods of accelerometers to provide future recommendations for the calibration and use of accelerometer devices.

METHODS: Data were captured from 16 Trigno sensors (Delsys, Natick, MA) simultaneously at a sampling rate of 148.1Hz in Cortex 7.2 software (Motion Analysis Corporation, Santa Rosa, CA). The sensors were attached using double-sided adhesive tape to a custom rig (Figure 1), which allowed the sensors to be positioned in any orientation. Data were captured from the rig positioned in 9 orientations (-1g and 1g in x, y and z axes also providing 0g values, and in three intermediate positions of midway between -x and y, x and -z, and -y and z). The position of the rig was determined using a 0.01° accurate 2D-spirit level (DXL360S). Data were analysed in Matlab (v2018a, Natick, MA) using custom written code.

Figure 1: Testing rig holding 16 sensors on the long arm, with the spirit-level in the middle.

The gravity based calibration was based on the premise that when the accelerometer is stationary then the resultant acceleration is equal to 1g (Equation 1), where: V is measured voltage; O is calculated voltage offset, and; S is calculated bias or scale. These V, O and S were obtained for each of the three Cartesian axes x, y and z of the accelerometer. Three methods were used to calculate O and S as described in equations 2 to 9 below.

$$1g = \sqrt{\left(\frac{V_x - O_x}{S_x}\right)^2 + \left(\frac{V_y - O_{xy}}{S_y}\right)^2 + \left(\frac{V_z - O_z}{S_z}\right)^2} \quad (1)$$

Calibration 1, denoted as 1G, involved 6 measurements for the accelerometer positioned at 0g and 1g for each of the x, y and z axes. The output voltage at 1g (V_{1g} = voltage output) and 0g (V_{0g} = voltage output) was entered into equations 2 to 3 (x direction shown, but repeated for y and z directions). Note, these 6 measurements can be obtained from 3 trials.

$$O_x = V_{0gx} \quad (2)$$

$$S_x = |V_{1gx} - V_{0gx}| \quad (3)$$

Calibration 2, denoted as 2G, involved 6 measurements for the accelerometer positioned at -1g and 1g for each of the x, y and z axes. The output voltage at -1g (V_{-1g} = voltage output) and 1g was entered into equations 4 to 5 (x direction shown, but repeated for y and z directions).

$$O_x = (V_{1gx} + V_{-1gx})/2 \quad (4)$$

$$S_x = |V_{1gx} - V_{-1gx}|/2 \quad (5)$$

Calibration 3, denoted as 2Gopt, involved 9 measurements for the accelerometer positioned in 9 positions, and used a Newtonian optimization (Frosio et al. 2009, Kumar, 2011) to determine O (Equation 6) and S (Equation 7). For greater speed in calculation, all 9 positions can be random, but instead 6 positions were those from the 2G methods above, and the remaining 3 were midway positions between -x and y, x and -z, and -y and z). The results from the 2G method from equations 4 and 5 were also used to provide the initial estimates for equation 6 and top-left to bottom-right diagonal of equation 7. Initial estimates for the remaining elements in equation 7 would ideally be 0 and were set to 0. This diagonal in equation 7 is the principal scaling factor, and the other elements are the cross-axis factors catering for any misalignment of axes and crosstalk. The difference between the known and calculated accelerations were quantified as the minimum, maximum and RMSD.

$$O = \begin{bmatrix} O_x \\ O_y \\ O_z \end{bmatrix} \tag{6}$$

$$S = \begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix} \tag{7}$$

Once O and S were optimised, the top-left to bottom-right diagonal of equation 8 provided the calibrated data (note, ○ indicates element by element multiplication of the matrices). Where, V is the sensor uncalibrated input voltage (Equation 9).

$$A = \begin{bmatrix} a_{xx} & a_{xy} & a_{xz} \\ a_{yx} & a_{yy} & a_{yz} \\ a_{zx} & a_{zy} & a_{zz} \end{bmatrix} = S \circ (V - O) \tag{8}$$

$$V = \begin{bmatrix} v_x & v_y & v_z \end{bmatrix} \tag{9}$$

RESULTS: The percentage error for the different methods (Table 1) indicates that the 1G had the greatest error, and that the 2G and 2Gopt were equally as good with RMSD of about 2.1%. In investigating the different axes (Figure 2), the greatest error was in z, then y and best in x. Zero error in Figure 2 represents the sensor orientation used in the calibration process. It is also possible to identify sensors with greater error, for instance this was greatest in the sensor numbers 8 (blue), 12 (green) and 13 (light blue) in x, y and z, respectively, suggesting no sensor was particularly problematic.

Table 1: Percentage error for three calibration methods (1G, 2G and 2Gopt).

	1G	2G	2Gopt
Minimum	-11.5	-5.46	-5.45
Maximum	11.7	8.67	8.65
RMSD	3.1	2.15	2.16
RMSD (cross-axis factors)	-	-	2.0

DISCUSSION: The error in the calibration of accelerometers is clearly influenced by the method of calibration. The 1G method had the greatest error (RMSD=3.1%; Max=11.7%), partly as the calculation is made over the shortest range of 1g. In doubling the range to 2g, the 2G method was just as simple, but more accurate (RMSD=2.15%; Max=8.67%). Both the 1G and 2G methods required only 6 trials, using 6 orientations, but the sensors must be precisely located in known positions related to gravity. The 2G method was equally as good as the 2Gopt method (RMSD=2.16%; Max=8.65%). The 2Gopt requires 9 trials, which theoretically could be random but when random trials were used a solution was not always found. However, by using extremes of positions (i.e. including the 6 trials required for the 2G method), then the optimisation solution was found rapidly.

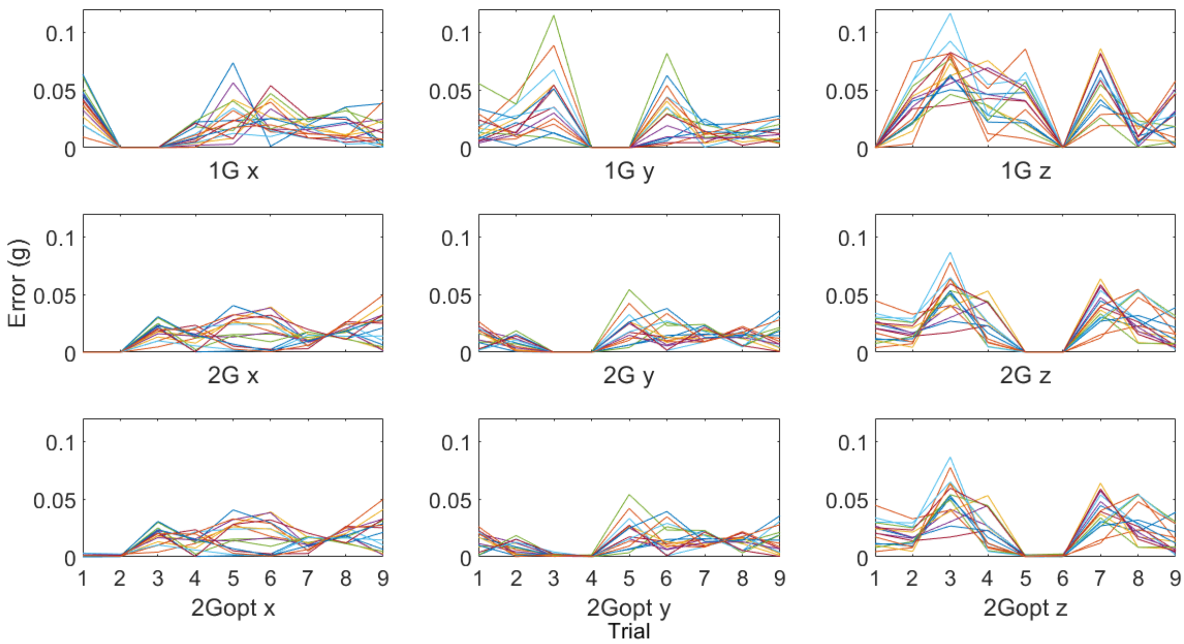

Figure 2: Error (g) in each of 16 sensors (coloured lines) for each axis (x, y and z) for three calibration procedures (1G, 2G and 2Gopt) across 9 trials (where trials are 1=-1gx, 2=1gx, 3=-1gy, 4=1gy, 5=-1gz, 6=1gz, 7=mid-1gx.1gy, 8=mid1gx. -1gz, 9=mid-1gy.1gz).

Even though random trials were not used in the 2Gopt method shown here, these trials do not have to be accurately positioned. The 2Gopt method has an additional advantage over the other methods in that cross-axis factors can be determined, and this was found to have a RMSD=2.0%. This provides some indications of cross-talk between sensor channels which may be meaningful when assessing the quality of sensor readings over time and also allow for accurate signal separation for acceleration orientation relative to an axis. This study has only compared three methods of simple gravity based calibration methods, and has limitations in the small range tested and does not provide any insight into factors including the translation of this to dynamic movements greater than 1g, the latency of response of sensors, maintenance of calibration throughout time, or effects of environmental conditions. Future research addressing these concerns would provide valuable information in determining the required frequency of calibration for applied use.

CONCLUSION: This study has shown that simple gravity based calibration of accelerometers can be achieved quickly, and that methods calibrating over a larger range (i.e. -1g to 1g) provide more accurate results. Both simple and more computationally advanced methods provide equally as good calibrations, hence instead a greater range is more important to obtain a good calibration. Many other factors influencing calibration need further investigation, including identifying the required frequency of calibration of accelerometers or similar devices.

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