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Title: The validity of using Inertial Measurement Units to monitor the torso and pelvis sagittal plane motion of elite rowers.

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Abstract

In elite sport, inertial measurement units (IMUs) are being used increasingly to measure movement in-field. IMU data commonly sought are body segment angles as this gives insights into how technique can be altered to improve performance and reduce injury risk. The purpose of this was to assess the validity of IMU use in rowing and identify if IMUs are capable of detecting differences in sagittal torso and pelvis angles that result from changes in stroke rates. Eight elite female rowers participated. Four IMUs were positioned along the torso and over the pelvis of each athlete. Reflective markers surrounded each IMU which were used to compute gold-standard data. Maxima, minima, angle range, and waveforms for ten strokes at rates of 20, 24, 28, and 32 strokes per minute were analysed. Root mean square errors as a percentage of angle range fell between 1.44 and 8.43%. In most cases when significant differences ($p < 0.05$) in the angles were detected between stroke rates, this was observed in both IMU and gold-standard angle data. These findings suggest IMUs are valid for measuring torso and pelvis angles when rowing, and are capable of detecting differences that result from changes in stroke rate.

Keywords: Rowing; Biomechanics; Engineering; Measurement

Introduction

Rowing is a demanding Olympic sport where success relies heavily on athletes moving in time with one another, and on the coordinated inter-joint movement of each individual (Buckeridge et al., 2015; Zainuddin et al., 2019). Performance is also reliant on the ability of each athlete to transfer the force they generate at the foot stretcher to the oar which is then used to propel the boat forward (Baudouin & Hawkins, 2002). The trunk plays an important role in the transmission of foot stretcher forces to the oar, and in linking the lower and upper extremities (Baudouin & Hawkins, 2002). For this reason, rowing spinal and pelvic kinematics and kinetics has received a lot of research attention (Buckeridge et al., 2015, 2016; Martinez-Valdes et al., 2019; McGregor et al., 2005; Trompeter et al., 2019; Wilson et al., 2013). A further reason for the focus on spinal and pelvic motion in the literature is that the back is the most common site of injury for elite rowers (Newlands et al., 2015; Smoljanovic et al., 2015; Trease et al., 2020).

Previous studies have found that rowers who suffer from low back pain exhibit greater pelvic rotation and have less efficient trunk muscle activity (Martinez-Valdes et al., 2019; McGregor et al., 2002; Nugent et al., 2021). Previous work has also found that as stroke rates increase there are increases in back injury risk factors which is specifically exhibited by increases in the shear and compressive forces in the lumbo-pelvic region (Buckeridge et al., 2016). Furthermore, stroke rate increases have also been associated with increases in the range of motion at the lumbo-pelvic, lumbar spine, and thoracic spine regions (Buckeridge et al., 2016; Li et al., 2020; Wilson et al., 2013) which can all have implications for loading on the back.

Most of the aforementioned studies have examined rowing on ergometers primarily due to the difficulties that surround measurement on-water. This is problematic as previous work has found that on-water rowing movements are significantly different to movements performed on an ergometer (Wilson et al., 2013). It would therefore be beneficial to athletes, coaches, and practitioners if data surrounding spinal and pelvic movement could be accurately collected on-water. One measurement device capable of this are portable electrogoniometers; however, many of these systems require bulky data loggers to be worn. Another measurement device being used increasingly to measure movements of athletes in-field are inertial measurement units (IMUs). IMUs are lightweight, small in size, and do not require additional data loggers to be worn. IMUs consist of accelerometers, gyroscopes, and magnetometers and the signals from these sensors can be combined using fusion algorithms (Kalman, 1960; Madgwick et al., 2011) to measure body segment motion.

Previous work has found that IMUs are valid for measuring segment motion and relative segment motion in a number of movements and sporting disciplines (Bergamini et al., 2013; Blair et al., 2018; Brice et al., 2018; Brice et al., 2020; Brouwer et al., 2020; Cottam et al., 2018; Faber et al., 2009; Hindle et al., 2020; Liu et al., 2020). Concerning work that has reported on the validity of IMUs for measuring sagittal plane relative angles, Brice et al. (2020) examined the relative angle between the torso and pelvis and found root mean square errors (RMSE) ranged between 2.9 ± 1.3° and 3.1 ± 1.5° depeding on the IMU's location on the spine. Concerning the work that has reported on the validity of IMUs for measuring sagittal plane segment motion, Bergamini et al. (2013) examined trunk inclination during the running sprint start and reported an RMSE of 3 ± 3° while Faber et al. (2009) reported an RMSE of 4.6 ± 2.9° when they investigated trunk inclination during a bent over lifting task. While numerous studies have found IMUs to be valid, it is noted that the degree of accuracy is site and task specific (Cuesta-Vargas et al., 2010) which is evident in the aforementioned studies. To our knowledge, one previous study has investigated the validity of IMU use in rowing (King et al., 2009). The findings of this study indicated that IMUs located over the pelvis and thoracolumbar (L1/T12) juncture can validly measure sagittal plane inclination angles; however, novice rowers were used in this study and stroke rate information was not reported. Given that novice rowers were analysed it is possible that the stroke rates used by the rowers in this study were below what elite rowers would commonly work at in training and competition. It is possible that as stroke rates increase the error in the IMU angles may change due to the increased movement speed. King et al. (2009) also investigated the impact of poor technique on IMU measured angles.

Visual inspection of the IMU waveforms was undertaken and differences were visible. Another study that used IMUs to assess differences in technique is that of Klitgaard et al. (2021) who examined the differences between elbow, shoulder, and knee angles when kayaking on-water versus on an egometer. Statically significant differences were evident in the IMU data that were collected for the two kayaking conditions. In both the aforementioned studies, there were no comparisons made between the IMU data and a gold-standard to assess if the differences that were evident in the IMU data were identical to that of a gold-standard. One previous study that did compare IMU angles with a gold-standard found IMUs are capable of detecting technique differences in shoulder and elbow flexion during canoeing (Liu et al., 2020). It would also be desirable to know if IMUs have the precision to be able to detect the changes in the spinal motion of rowers that are detected by gold-standard 3D motion capture systems.

The purpose of this present study was two-fold. The first aim was to assess the validity of the IMeasureU (Oxford Metrics, Oxford, UK) IMUs for measuring sagittal plane motion of the spine and pelvis when rowing at different stroke rates. The second aim was to examine if the IMUs were capable of detecting if and when there were differences in the angle between stroke rates.

Materials and Methods

Eight elite female rowers participated in this study which was given ethical approval by the James Cook University Human Research Ethics Committee. All eight were national team members and competing at an international level at the time of data collection. Prior to data collection, all subjects gave written informed consent. A priori sample size calculation with an alpha level of 0.05 found that seven participants was sufficient to generate statistical power of 80% with a large effect size.

Participants performed a self-selected warm-up and then rowed continuously for seven minutes on an ergometer (Concept 2, Morrisville, VT, USA). Before rowing commenced each participant sat in an upright stationary position on the ergometer. The angle of the spine relative to the vertical in this position was then defined as zero degrees. Participants rowed for one minute at rates of 20, 24, 28, and 32 strokes per minute. These stroke rates were chosen as they are reflective of the rates used during the incremental "step test" which is commonly used to monitor the training levels and fitness of rowers, and are reflective of a range of normal training intensities (McGregor et al., 2005). Between each increment, participants rowed for one minute at 18 strokes per minute for active recovery. Each participant had four IMeasureU IMUs v2.0 (Oxford Metrics, Oxford, UK) positioned on their back and pelvis. Each IMU consisted of tri-axial accelerometers (± 16 g), gyroscopes (± 2000 °/s), and magnetometers (± 1200 mT). The average maximum angular speed of the rowing motion measured in this study was 288 ± 62°/s which is well below the range specified by the manufacturers. IMUs were located over the spinous processes of the first thoracic (T1 sensor), seventh thoracic (T7 sensor), second lumbar (L2 sensor), and second sacral (S2 sensor) vertebrae. The T1, T7, and L2 sensors were mounted on rigid plastic boards with three retro-reflective markers surrounding them. The S2 sensor was skin mounted with three markers positioned around it. The S2 sensor and markers were not placed on a plastic board as this part of the pelvis is flat. The markers were used to compute the gold-standard angle data.

Throughout the seven minutes of rowing, IMU data was logged to an on-board SD card at 500Hz. The IMUs were used in accordance with the manufacturer's instructions and were operated and synchronised using the manufacturer's custom applications. When the participants were rowing at stroke rates of 20, 24, 28, and 32 strokes per minute, marker location data were also collected at 250Hz. Marker locations were collected using a 14 Vicon Vantage camera system and the Vicon Nexus v2.8 software (Oxford Metrics, Oxford, UK). A fifth IMU (sync IMU) was used during data collection to allow motion capture and IMU data to be synchronized during post-processing. This involved aligning magnetic pulses from an electromagnet that were collected by the analogue input of the motion capture system and the sync IMU (Brice et al., 2020).

Marker data were filtered in Vicon Nexus using a Woltring filter with a mean standard error of 9 mm. This filter level was determined via a residual analysis (Winter, 2009). IMU data were processed using custom Matlab scripts (Mathworks, Natic, USA). Firstly, the magnetometers were calibrated using an ellipsoid fitting procedure. General descriptions of this procedure have previously been reported (Gebre-Egziabher, 2007; Li & Li, 2012). However, in our implementation, the fitting was constrained to find only ellipsoids whose principal axes align with the IMU's axes, because we found that restricting the fitting in this way increased its robustness when the magnetometer had not been fully rotated through all possible angles during the data collection. These constrained ellipsoids correct for "hard iron" offsets in 3 axes, and scale factor adjustments in 3 axes. The Kalman filter uses two reference vectors to define the IMU orientation relative to a fixed laboratory reference frame. These two reference vectors are the direction of gravity and the direction of the Earth's magnetic field. Gravity was taken to be along the lab's Z axis. For the magnetic field reference, we extracted the magnetic field as measured by each sensor during the initial part of each trial where the participants were stationary on the ergometer. Each sensor measures the magnetic field in its own reference frame, so we converted from the sensor's frame to the lab frame by rotating the measured magnetic field using the orientation extracted from the Vicon system at the same moment in time. The result was the Earth's magnetic field in the Vicon coordinate system according to each of the IMUs. We then averaged over all sensors to give a single reference vector for the direction of the magnetic field in the laboratory reference frame.

Since the parameter of interest was spinal flexion and extension, we extracted a scalar angle from the 3D orientation of each sensor as shown in Figure 1. The angle of each sensor was calculated as the angle between the lab Z axis and the sensor's Y axis, as indicated by the angle θ in Figure 1. This angle was calculated using

$$\theta = \mathrm{atan}\frac{\boldsymbol{y}_Y}{\boldsymbol{y}_Z},$$

where $\boldsymbol{y}_Y$ and $\boldsymbol{y}_Z$ are the projection of the IMU y axis onto the lab Y and Z axes, respectively. Angle calculations were performed separately for the Vicon data and the IMU data, resulting in two different measurements of the same angle at every time step in the recording. Finally, an anatomically neutral angle of 0° was defined as the position that each participant adopted when they were seated stationary on the ergometer (see Table 1 for the mean angles of the spine in this position). All angles are reported relative to this neutral position. It should be noted that the sagittal plane angle calculated here is not calculated in the same manner as an anatomical marker based model in a global reference frame. This has been noted previously in the literature (Brice et al., 2020; Cottam et al. 2018).

[Figure 1 near here]

[Table 1 near here]

Ten complete strokes at the mid-point of the 20, 24, 28, and 32 stroke rate intervals were selected for analysis. The maximum, minimum, and range of the sagittal plane inclination for each stroke was determined for the four IMU locations. For each sensor location a total of 80 data points (eight athletes x ten strokes) for each discrete variable at each stroke rate were examined. Discrete angle values were analysed as rowing literature that has examined spinal motion has previously focused on examining discrete angle values. In addition to examining discrete variables, the entire waveform for each participant's ten strokes at each stroke rate was also examined. While waveforms of spinal angles have not been looked at in depth in the literature, waveforms of other variables such as oar angle have been examined in rowing (Warmenhoven et al., 2017). For the discrete variables, the root mean square error (RMSE) and RMSE as a percentage of angle range (RMSE%) were determined, at each IMU location, for each stroke rate (Bauer et al., 2015). 95% confidence intervals (CI_{Lower} and CI_{Upper}) were also determined for RMSE. Bland-Altman biases and 95% limits of agreement (LOA_{Upper} and LOA_{Lower}) were also computed (Bland & Altman, 1986). For each ten stroke waveform the aforementioned comparison measures were determined. The comparison measures were then averaged for each sensor for each of the stroke rates (Brice et al., 2020).

For each athlete, the average of the maximum angle, minimum angle, and angle range for each stroke rate was determined for each sensor (i.e. average of the ten strokes examined). A repeated measures ANOVA was then used to assess for a main effect of stroke rate for each variable. The level of significance was set at $p < 0.05$. When significant main effects were detected F values, p values, and effect sizes (partial η^2) were reported (Bakeman, 2005). The effect sizes were classified as trivial (<0.0099), small (0.0099 – 0.0587), moderate (0.0588 – 0.1378), and large (≥0.1379) (Cohen, 1988). Where there were main effects detected, post-hoc tests with a Bonferroni adjustment were used to identify where the differences were and adjusted p values and effect sizes (Cohen's d) were reported. The adjusted effect sizes were classified as trivial (0 – 0.19), small (0.20 – 0.49), moderate (0.50 – 0.79), and large (≥0.80)

(Cohen, 1988). This was done to assess if the IMUs were capable of identifying changes in the maximum, minimum, and range of the angle between the stroke rates if they were present.

Results

There was strong agreement between the angles measured using the IMUs and the motion capture system (Table 2a and 2b; Figure 2-5). Considering first the discrete values, RMSE values ranged from between 1.05° and 4.90° with the average being 2.29 ± 0.97°. RMSE% values ranged from 1.44% to 8.43% with the average being 3.93 ± 1.99%. Bland-Altman biases ranged from -3.09° to 2.87° with the average being 1.31 ± 0.21°. In most cases the biases were positive which indicates the IMUs generally overestimated the maximum, minimum, and range of the angle at each sensor location (Table 2a and 2b). Considering the waveforms, RMSE values ranged from between 1.19° and 3.77° with the average being 2.16 ± 0.93°. RMSE% values ranged from 1.55% to 7.11% with the average being 3.79 ± 2.24%. Bland-Altman biases ranged from -0.91° to 1.51° with the average being -0.02 ± 0.72°. In most cases the biases were negative which indicates that for the overall waveform the IMUs slightly underestimated the angle at each sensor location.

[Table 2a near here]

[Table 2b near here]

[Figure 2 near here]

[Figure 3 near here]

[Figure 4 near here]

[Figure 5 near here]

Assessment of whether the IMUs were capable of identifying if and when stroke rate significantly altered the maximum, minimum, and range of the angles revealed that the IMUs had similar results to that of the gold-standard 3D motion capture system's measurements. There were three instances for both gold-standard and IMU angles where main effects of stroke rate were observed. A main effect was observed in the minima for T1 (gold-standard: $F = 6.861$, $p = 0.026$, partial $\eta^2 = 0.533$ [large] and IMU: $F = 7.455$, $p = 0.017$, partial $\eta^2 = 0.554$ [large]), in the minima for T7 (gold-standard: $F = 6.021$, $p = 0.005$, partial $\eta^2 = 0.501$ [large] and IMU: $F = 3.614$, $p = 0.033$, partial $\eta^2 = 0.376$ [large]), and in the maxima for T7 (gold-standard: $F = 21.211$, $p = 0.000$, partial $\eta^2 = 0.780$ [large] and IMU $F = 13.236$, $p = 0.000$, partial $\eta^2 = 0.688$ [large]). Where main effects were observed, post-hoc testing results revealed the following for both the 3D motion capture angles and the IMU angles (Table 3):

- T1 minima were significantly greater for step 24 than steps 28 and 32
- T7 minima were significantly greater for step 24 than steps 28 and 32.
- T7 maxima were significantly smaller for step 20 than steps 28 and 32
- T7 maxima were significantly smaller for step 24 than step 32

There was one post-hoc testing result observed for 3D motion capture angles that was not observed for the IMU angles which was that T7 maxima were significantly smaller for step 28 than step 32 (Table 3).

[Table 3 near here]

Discussion

The purpose of this investigation was two-fold. The first aim was to assess the validity of the IMeasureU IMUs for measuring torso and pelvis sagittal plane inclination when rowing at different stroke rates. Sagittal plane inclination at three torso locations (T1, T7, and L1) and the pelvis (S2) for four different stroke rates (20, 24, 28, and 32 strokes per minute) was measured. Ten strokes at each stroke rate for each athlete were examined. For each stroke the angle's maximum, minimum, and range were determined. Discrete angle validity was assessed by comparing maximum, minimum, and range for each stroke measured by the IMUs at each location with angles measured by a 3D motion capture system (gold-standard). For the entire ten strokes measured at each sensor location for each athlete, the waveforms were also examined for all four stroke rates. Like the discrete variables, waveform validity was assessed by comparing the ten stroke waveforms measured by the IMUs and the 3D motion capture system waveforms at each sensor location. The second aim was to examine if the IMUs were capable of identifying if and when stroke rate significantly altered the angles. This was assessed by comparing the average of each athlete's maximum, minimum, and range at each sensor location for each stroke rate.

Concerning the first aim, it has been reported that for a measurement system to be considered valid RMSE% values should be below 10% (Walgaard et al., 2016) and RMSE values should be below 5° (McGinley et al., 2009). All RMSE% and RMSE values were below these limits (Table 2a and b) which indicates that the IMUs are valid for measuring sagittal plane trunk inclination during rowing. The level of agreement that we observed is similar to what has been observed by others who have also examined IMU use for measuring trunk inclination relative to the vertical during sporting activities (Bergamini et al., 2013; King et al., 2009). The level of agreement we observed is slightly lower than what has been observed with electromagnetic devices (Bull & McGregor, 2000); however, these devices are constrained to the laboratory environment which is a limitation that IMUs overcome. To our knowledge only one previous study (King et al., 2009) has attempted to validate IMU use in rowing. In this previous study novice rowers were examined and IMUs were located at the L1/T12 juncture and on the pelvis.

An average error of 3.98° was observed at L1/T12 while the error at the pelvis was slightly higher at 4.08°. We also observed that the pelvis IMUs error was slightly higher (Table 2a and 2b). In the previous study they did not report the stroke rate of the novice rowers which was noted in our introduction as a limiting factor. Novice rowers may not row at the rates expected of elite athletes and differences in movement speed may impact on IMU validity. In our study we addressed this by investigating a number of stroke rates and found that stroke rate did not impact on the accuracy of the IMUs. This provides confidence to practitioners that IMUs are a suitable device to use in the assessment and monitoring of torso and pelvis motion in training and competition where varied stroke rates occur.

Concerning the second aim of our study, the IMUs and 3D motion capture system detected identical main effects of stroke rate on the maxima at T7 and the minima at T1 and T7. Post-hoc tests further revealed that all findings were identical with the exception being that for the 3D motion capture data the T7 maxima were significantly smaller for step 28 than step 32 (Table 3). It should be noted that while not significant, an identical trend was present for the step 28 and 32 T7 IMU maxima (Table 3). These findings suggest that the IMUs examined in this study are capable of detecting differences in technique; however, care should be taken particularly when using an IMU located at T7. To our knowledge one previous study has examined whether the IMU traces for different rowing techniques are different. King et al. (2009) provided novice rowers with examples of good technique and two types of bad technique. The participants were then instructed to row with the three techniques they had been shown. Angle traces from IMUs located at the L1/T12 juncture and over the pelvis were compared to see if visual differences were present in the waveforms. Visually the waveforms looked different (predominantly at the maxima); however, there was no comparison with gold-standard angles and the waveforms of single participant were presented. Despite this King et al. (2009) claim that the IMUs were capable of identifying differences in technique which our statistical analysis supports.

It should be noted that our study had some limiting factors. First, a small number of athletes were used. Care should be taken particularly when drawing conclusions from our between stroke rate comparisons of the angles we measured. It is also possible that the errors we observed may have been different had a larger sample been examined, although nearly all 95% confidence interval upper limits were below values reported as being acceptable in the literature. Second, we carried out our validation on an ergometer. It should be noted that the error in the IMU angles may be different when rowing on-water and future work should attempt to validate IMU use on-water to assess if the error is significantly different to what is observed on an ergometer. Third, while we did examine stroke rates that are reflective of the different training intensities (McGregor et al., 2005), others have found even higher stroke rates can be used in competition (Silva et al., 2020). For all stroke rates we investigated we did find that the IMUs were valid and future work should consider confirming that the IMUs continue to be valid when using higher stroke rates.

Conclusion

This study investigated the accuracy of sagittal plane torso and pelvis angle data collected using IMUs when rowing at four different stroke rates. The angles measured by the IMUs were found to be highly valid as there was close agreement between IMU angles and those measured using the gold-standard 3D motion capture system. We also investigated whether the IMUs were capable of detecting if and when differences in stroke rate altered the sagittal plane angles. We found that in most instances significant differences detected in the gold-standard angles were also detected in the IMU angles. Our work suggests that IMUs are a viable option for measuring accurate sagittal plane angle data during rowing.

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Declaration of interest statement:

The authors report no conflict of interest.

References

Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior research methods*, *37*(3), 379-384. https://doi.org/10.3758/BF03192707

Baudouin, A., & Hawkins, D. (2002). A biomechanical review of factors affecting rowing performance. *British Journal of Sports Medicine*, *36*(6), 396-402. https://doi.org/10.1136/bjsm.36.6.396

Bauer, C. M., Rast, F. M., Ernst, M. J., Kool, J., Oetiker, S., Rissanen, S. M., Suni, J. H., & Kankaanpää, M. (2015). Concurrent validity and reliability of a novel wireless inertial measurement system to assess trunk movement. *Journal of Electromyography and Kinesiology*, *25*(5), 782-790. https://doi.org/http://dx.doi.org/10.1016/j.jelekin.2015.06.001

Bergamini, E., Guillon, P., Camomilla, V., Pillet, H., Skalli, W., & Cappozzo, A. (2013). Trunk inclination estimate during the sprint start using an inertial measurement unit: A Validation Study. *Journal of Applied Biomechanics*, *29*(5), 622-627. https://doi.org/10.1123/jab.29.5.622

Blair, S., Duthie, G., Robertson, S., Hopkins, W., & Ball, K. (2018). Concurrent validation of an inertial measurement system to quantify kicking biomechanics in four football codes. *Journal of Biomechanics*, *73*, 24-32. https://doi.org/https://doi.org/10.1016/j.jbiomech.2018.03.031

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, *1*. 307-310 https://doi.org/10.1016/s0140-6736(86)90837-8

Brice, S. M., Hurley, M., & Phillips, E. J. (2018). Use of inertial measurement units for measuring torso and pelvis orientation, and shoulder–pelvis separation angle in the discus throw. *International Journal of Sports Science & Coaching*, *13*(6), 985-992. https://doi.org/10.1177/1747954118778664

Brice, S. M., Phillips, E. J., Millett, E. L., Hunter, A., & Philippa, B. (2020). Comparing inertial measurement units and marker-based biomechanical models during dynamic rotation of the torso. *European Journal of Sport Science*, *20*(6), 767-775. https://doi.org/10.1080/17461391.2019.1666167

Brouwer, N., Yeung, T., Bobbert, M., & Besier, T. (2020). 3D trunk orientation measured using inertial measurement units during anatomical and dynamic sports motions. *Scandinavian Journal of Medicine & Science in Sports*, *31*(2), 1-13. https://doi.org/10.1111/sms.13851

Buckeridge, E. M., Bull, A. M. J., & McGregor, A. H. (2015). Biomechanical determinants of elite rowing technique and performance. *Scandinavian Journal of Medicine & Science in Sports*, *25*(2), e176-e183. https://doi.org/10.1111/sms.12264

Buckeridge, E. M., Bull, A. M. J., & McGregor, A. H. (2016). Incremental training intensities increases loads on the lower back of elite female rowers. *Journal of Sports Sciences*, *34*(4), 369-378. https://doi.org/10.1080/02640414.2015.1056821

Bull, A. M. J., & McGregor, A. H. (2000). Measuring spinal motion in rowers: the use of an electromagnetic device. *Clinical biomechanics*, *15*(10), 772-776. https://doi.org/10.1016/S0268-0033(00)00043-7

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.

Cottam, D., Kosovich, S., Campbell, A., Davey, P., Kent, P., Tan, J.-S., Elliott, B., & Alderson, J. (2018, September). Can inertial measurement units be used to measure pelvis and thorax motion during cricket. In P. Hume, J. Alderson, & B. Wilson (Eds.), *Proceedings of the 36th International Conference of Biomechanics in Sports* (pp 350-353). International Society of Biomechanics in Sport. Retrieved from https://commons.nmu.edu/isbs/vol36/iss1/66/

Cuesta-Vargas, A. I., Galán-Mercant, A., & Williams, J. M. (2010). The use of inertial sensors system for human motion analysis. *Physical Therapy Reviews*, *15*(6), 462-473. https://doi.org/10.1179/1743288X11Y.0000000006

Faber, G. S., Kingma, I., Bruijn, S. M., & van Dieën, J. H. (2009). Optimal inertial sensor location for ambulatory measurement of trunk inclination. *Journal of Biomechanics*, *42*(14), 2406-2409. https://doi.org/https://doi.org/10.1016/j.jbiomech.2009.06.024

Gebre-Egziabher, D. (2007). Magnetometer Autocalibration Leveraging Measurement Locus Constraints. *Journal of Aircraft*, *44*(4), 1361-1368. https://doi.org/10.2514/1.27118

Hindle, B. R., Keogh, J. W. L., & Lorimer, A. V. (2020). Validation of Spatiotemporal and Kinematic Measures in Functional Exercises Using a Minimal Modeling Inertial Sensor Methodology. *Sensors*, *20*(16), Article 4586. https://www.mdpi.com/1424-8220/20/16/4586

Kalman, R. E. (1960). A New Approach to Linear Filtering and Prediction Problems. *Journal of Basic Engineering*, *82*(1), 35-45. https://doi.org/10.1115/1.3662552

King, R. C., McIlwraith, D. G., Lo, B., Pansiot, J., McGregor, A. H., & Yang, G. (2009, June). Body Sensor Networks for Monitoring Rowing Technique. In P.K Wright, & E.M.Yeatman (Eds.) *Proceedings of the 6th International Workshop on Wearable and Implantable Body Sensor Networks* (pp. 251-255). Institute of Electrical and Electronics Engineers. Retrieved from https://doi: 10.1109/BSN.2009.60

Klitgaard, K. K., Hauge, C., Oliveira, A. S., & Heinen, F. (2021). A kinematic comparison of on-ergometer and on-water kayaking. *European Journal of Sport Science*, *21*(10), 1375-1304. https://doi.org/10.1080/17461391.2020.1831617

Li, Y., Koldenhoven, R. M., Jiwan, N. C., Zhan, J., & Liu, T. (2020). Trunk and shoulder kinematics of rowing displayed by Olympic athletes. *Sports Biomechanics*. Advance online publication. https://doi.org/10.1080/14763141.2020.1781238

Li, X., & Li, Z. (2012). A new calibration method for tri-axial field sensors in strap-down navigation systems. *Measurement Science and Technology*, *23*(10), 105105. https://doi.org/10.1088/0957-0233/23/10/105105

Liu, L., Qiu, S., Wang, Z., Li, J., & Wang, J. (2020). Canoeing Motion Tracking and Analysis via Multi-Sensors Fusion. *Sensors*, *20*(7), 2110. https://doi.org/10.3390/s20072110

Madgwick, S. O. H., Harrison, A. J. L., & Vaidyanathan, R. (2011, June-July). Estimation of IMU and MARG orientation using a gradient descent algorithm. In R. Gassert, J. Herder, S. Micera, R. Riener, & P. Wolf (Eds.), *Proceedings of the 2011 IEEE International Conference on Rehabilitation Robotics* (pp. 1-7). Institute of Electrical and Electronics Engineers. Retrieved from https://doi: 10.1109/ICORR.2011.5975346.

Martinez-Valdes, E., Wilson, F., Fleming, N., McDonnell, S.-J., Horgan, A., & Falla, D. (2019). Rowers with a recent history of low back pain engage different regions of the lumbar erector spinae during rowing. *Journal of Science and Medicine in Sport*, *22*(11), 1206-1212. https://doi.org/http://dx.doi.org/10.1016/j.jsams.2019.07.007

McGinley, J. L., Baker, R., Wolfe, R., & Morris, M. E. (2009). The reliability of three-dimensional kinematic gait measurements: a systematic review. *Gait Posture*, *29*(3)*, 360–369*. https://doi.org/10.1016/j.gaitpost.2008.09.003

McGregor, A. H., Anderton, L., & Gedroyc, W. M. W. (2002). The trunk muscles of elite oarsmen. *British Journal of Sports Medicine*, *36*(3), 214-217. https://doi.org/10.1136/bjsm.36.3.214

McGregor, A. H., Patankar, Z. S., & Bull, A. M. J. (2005). Spinal kinematics in elite oarswomen during a routine physiological "step test". *Medicine and Science in Sports and Exercise*, *37*(6), 1014-1020. https://doi.org/10.1249/01.mss.0000171618.22263.58

Newlands, C., Reid, D., & Parmar, P. (2015). The prevalence, incidence and severity of low back pain among international-level rowers. *British Journal of Sports Medicine*, *49*(14), 951-956. https://doi.org/10.1136/bjsports-2014-093889

Nugent, F. J., Vinther, A., McGregor, A., Thornton, J. S., Wilkie, K., & Wilson, F. (2021). The relationship between rowing-related low back pain and rowing biomechanics: a systematic review. *British Journal of Sports Medicine*. *55*(11), 616-630. https://doi.org/10.1136/bjsports-2020-102533

Silva, F. B. M. d., Brito, J. P. R. G. M. d., & Gomes, A. C. (2020). Olympic rowing: model of competitive activity of international level elite female athletes. *Revista brasileira de medicina do esporte*, *26*(2), 162-166. https://doi.org/10.1590/1517-869220202602218337

Smoljanovic, T., Bohacek, I., Hannafin, J. A., Terborg, O., Hren, D., Pecina, M., & Bojanic, I. (2015). Acute and chronic injuries among senior international rowers: a cross-sectional study. *International Orthopaedics*, *39*(8), 1623-1630. https://doi.org/10.1007/s00264-014-2665-7

Trease, L., Wilkie, K., Lovell, G., Drew, M., & Hooper, I. (2020). Epidemiology of injury and illness in 153 Australian international-level rowers over eight international seasons. *British Journal of Sports Medicine*, *54*(21), 1288-1293. https://doi.org/10.1136/bjsports-2019-101402

Trompeter, K., Weerts, J., Fett, D., Firouzabadi, A., Heinrich, K., Schmidt, H., Brüggemann, G.-P., & Platen, P. (2019). Spinal and Pelvic Kinematics During Prolonged Rowing on an Ergometer vs. Indoor Tank Rowing. *Journal of Strength and Conditioning Research. 35*(9), 2622-2628. https://doi.org/10.1519/JSC.0000000000003187

Walgaard, S., Faber, G. S., van Lummel, R. C., van Dieën, J. H., & Kingma, I. (2016). The validity of assessing temporal events, sub-phases and trunk kinematics of the sit-to-walk movement in older adults using a single inertial sensor. *Journal of Biomechanics*, *49*(9), 1933-1937. https://doi.org/http://dx.doi.org/10.1016/j.jbiomech.2016.03.010

Wilson, F., Gissane, C., Gormley, J., & Simms, C. (2013). Sagittal plane motion of the lumbar spine during ergometer and single scull rowing. *Sports Biomechanics*, *12*(2), 132-142. https://doi.org/10.1080/14763141.2012.726640

Winter, D. A. (2009). *Biomechanics and motor control of human movement* (4th ed.). John Wiley & Sons, Inc.

Warmenhoven, J., Cobley, S., Draper, C., Harrison, A. J., Bargary, N., & Smith, R. (2017). Assessment of propulsive pin force and oar angle time-series using functional data analysis in on-water rowing. *Scandinavian Journal of Medicine & Science in Sports*, *27*(12), 1688-1696. https://doi.org/10.1111/sms.12871

Zainuddin, F. L., Zahiran, A., Umar, M. A., Shaharudin, S., & Razman, R. M. (2019). Changes in lower limb kinematics coordination during 2000m ergometer rowing among male junior national rowers. *Journal of Physical Education and Sport*, *19*(3), 1656-1662. https://doi.org/http://dx.doi.org/10.7752/jpes.2019.03240

Table 1. Mean angle of the spine relative to the vertical for the participants while seated on the ergometer measured by the IMUs and by the 3D motion capture system (gold-standard data - GS). For the rowing trials, the spine was defined as being in 0° in this position. Standard deviations are indicated in brackets.

	Location			
	T1	T7	L1	S2
GS angle (°)	34.55 (6.43)	12.20 (9.25)	-5.38 (9.96)	-13.95 (8.41)
IMU angle (°)	34.96 (6.19)	10.53 (10.30)	-5.86 (11.82)	-12.09 (3.52)

Table 2a: Comparison between maximum, minimum, range, and waveforms of the angles measured by the IMUs and by the 3D motion capture system (gold-standard data) for stroke rates 20 and 24. Standard deviations are indicated in brackets for the waveform values.

		Rate 20				Rate 24			
		T1	T7	L1	S2	T1	T7	L1	S2
Max	RMSE (°)	1.88	1.55	1.23	3.74	2.21	1.71	1.37	4.12
	RMSE CI_{Lower} (°)	1.63	1.34	1.07	3.24	1.91	1.48	1.19	3.57
	RMSE CI_{Upper} (°)	2.22	1.83	1.46	4.42	2.61	2.02	1.62	4.87
	RMSE%	4.34	1.98	1.70	6.48	5.15	2.13	1.82	7.09
	Bias (°)	-1.05	0.94	0.49	-2.30	-0.85	0.89	0.68	-3.09
	LOA_{Upper} (°)	2.02	3.36	2.72	3.54	3.17	3.77	3.03	2.31
	LOA_{Lower} (°)	-4.13	-1.48	-1.74	-8.15	-4.88	-1.99	-1.67	-8.48
Min	RMSE (°)	1.75	1.73	1.05	3.72	1.77	1.85	1.11	3.68
	RMSE CI_{Lower} (°)	1.52	1.50	0.91	3.22	1.53	1.60	0.96	3.19
	RMSE CI_{Upper} (°)	2.07	2.05	1.24	4.40	2.09	2.18	1.31	4.35
	RMSE%	4.04	2.22	1.44	6.44	4.12	2.30	1.47	6.33
	Bias (°)	0.97	0.15	0.34	2.85	0.93	0.21	0.32	0.21
	LOA_{Upper} (°)	3.84	3.56	2.30	7.57	3.89	3.83	-1.77	7.53
	LOA_{Lower} (°)	-1.89	-3.26	-1.62	-1.87	-2.03	-3.41	2.41	-7.12
Range	RMSE (°)	1.63	2.07	1.71	3.38	1.52	2.29	1.79	4.90
	RMSE CI_{Lower} (°)	1.41	1.79	1.48	2.92	1.31	1.98	1.55	4.24
	RMSE CI_{Upper} (°)	1.93	2.44	2.02	3.99	1.80	2.71	2.12	5.79
	RMSE%	3.77	2.65	2.35	5.85	3.54	2.85	2.37	8.43
	Bias (°)	-0.08	1.09	0.83	0.55	0.08	1.10	1.00	-2.88
	LOA_{Upper} (°)	3.14	4.55	3.77	7.18	3.07	5.06	3.93	0.02
	LOA_{Lower} (°)	-3.29	-2.37	-2.11	-6.09	-2.92	-2.87	-1.93	-5.78
Waveform	RMSE (°)	1.85 (0.87)	1.26 (0.37)	1.19 (0.57)	3.77 (0.50)	2.05 (0.94)	1.31 (0.38)	2.05 (0.94)	3.63 (0.81)
	RMSE CI_{Lower} (°)	1.82 (0.85)	1.24 (0.36)	1.18 (0.56)	3.71 (0.49)	2.02 (0.92)	1.29 (0.38)	1.39 (0.81)	3.56 (0.79)
	RMSE CI_{Upper} (°)	1.88 (0.88)	1.28 (0.37)	1.21 (0.56)	3.83 (0.50)	2.09 (0.95)	1.34 (0.39)	1.44 (0.84)	3.69 (0.82)
	RMSE%	3.99 (2.21)	1.51 (0.41)	4.33 (1.26)	7.11 (0.64)	4.45 (1.47)	1.57 (0.43)	4.45 (1.47)	6.83 (1.75)
	Bias (°)	-0.82 (1.14)	0.16 (0.35)	-0.23 (0.71)	0.94 (1.90)	-0.79 (1.38)	0.00 (0.50)	-0.06 (0.60)	1.19 (0.97)
	LOA_{Lower} (°)	-3.56 (1.65)	-2.19 (0.85)	-2.23 (1.34)	-5.49 (2.34)	-3.75 (1.52)	-2.41 (0.88)	-2.60 (1.94)	-5.30 (1.90)
	LOA_{Upper} (°)	1.91 (1.65)	2.51 (0.81)	1.76 (0.88)	7.36 (1.55)	2.17 (2.32)	2.41 (0.95)	2.48 (1.46)	7.68 (1.99)

Table 2b: Comparison between maximum, minimum, range, and waveforms of the angles measured by the IMUs and by the 3D motion capture system (gold-standard data) for stroke rates 28 and 32. Standard deviations are indicated in brackets for the waveform values.

		Rate 28				Rate 32			
		T1	T7	L1	S2	T1	T7	L1	S2
Max	RMSE (°)	2.01	1.84	1.47	2.58	2.64	2.24	1.22	4.22
	RMSE CI_{Lower} (°)	1.74	1.59	1.30	2.23	2.28	1.94	1.06	3.66
	RMSE CI_{Upper} (°)	2.38	2.17	1.74	3.05	3.11	2.66	1.45	4.99
	RMSE%	4.92	2.32	1.97	4.65	6.78	2.84	1.65	7.33
	Bias (°)	0.05	1.05	0.62	-2.70	-0.26	0.55	0.39	-2.62
	LOA_{Upper} (°)	4.02	4.03	3.26	1.17	4.92	4.85	2.68	3.94
	LOA_{Lower} (°)	-3.91	-1.93	-2.03	-6.57	-5.44	-3.75	-1.89	-9.18
Min	RMSE (°)	1.72	1.92	1.34	4.00	2.66	2.32	1.58	3.14
	RMSE CI_{Lower} (°)	1.49	1.67	1.16	3.47	2.31	2.01	1.37	2.72
	RMSE CI_{Upper} (°)	2.04	2.27	1.58	4.74	3.15	2.75	1.87	3.71
	RMSE%	4.22	2.43	1.79	7.22	6.86	2.94	2.14	5.45
	Bias (°)	0.77	0.42	0.29	-0.09	0.74	0.59	0.46	2.87
	LOA_{Upper} (°)	3.81	4.12	2.87	7.86	5.77	5.02	3.44	5.85
	LOA_{Lower} (°)	-2.27	-3.28	-2.29	-8.04	-4.30	-3.85	-2.53	-0.11
Range	RMSE (°)	1.99	2.30	1.97	4.38	1.36	2.94	1.76	2.43
	RMSE CI_{Lower} (°)	1.71	1.99	1.70	3.79	1.18	2.54	1.53	2.10
	RMSE CI_{Upper} (°)	2.35	2.72	2.33	5.18	1.61	3.47	2.08	2.87
	RMSE%	4.87	2.90	2.63	7.89	3.51	3.72	2.39	4.22
	Bias (°)	0.82	1.47	0.91	-2.79	0.69	1.14	0.85	0.25
	LOA_{Upper} (°)	4.40	4.95	4.36	5.89	3.07	6.48	3.90	3.84
	LOA_{Lower} (°)	-2.75	-2.02	-2.54	-11.47	-1.69	-4.21	-2.20	-3.33
Waveform	RMSE (°)	2.44 (1.19)	1.76 (0.59)	1.47 (0.78)	3.14 (1.06)	2.45 (1.00)	1.72 (0.57)	1.31 (0.39)	3.73 (1.47)
	RMSE CI_{Lower} (°)	2.40 (1.17)	1.73 (0.58)	1.44 (0.77)	3.08 (1.04)	2.40 (0.98)	1.67 (0.56)	1.28 (0.38)	3.66 (1.44)
	RMSE CI_{Upper} (°)	2.49 (1.21)	1.80 (0.60)	1.49 (0.80)	3.20 (1.08)	2.50 (1.02)	1.75 (0.58)	1.34 (0.40)	3.81 (1.50)
	RMSE%	5.48 (2.94)	2.12 (0.68)	1.84 (0.87)	6.02 (2.31)	5.61 (2.62)	2.05 (0.62)	1.66 (0.43)	7.01 (2.71)
	Bias (°)	-0.91 (1.60)	-0.03 (0.53)	-0.16 (0.79)	0.32 (0.73)	-0.85 (1.15)	-0.24 (0.46)	-0.28 (0.82)	1.51 (1.76)
	LOA_{Lower} (°)	-4.43 (1.95)	-3.32 (1.35)	-2.68 (2.03)	-5.68 (1.70)	-4.82 (1.99)	-3.48 (1.11)	-2.38 (1.17)	-4.73 (1.42)
	LOA_{Upper} (°)	2.61 (3.13)	3.26 (1.38)	2.37 (1.13)	6.32 (2.57)	3.11 (2.57)	3.01 (1.22)	1.82 (0.59)	7.75 (3.57)

Table 3. Means of the maximum, minimum, and range of the gold-standard (GS) and IMU angles at each stroke rate for all eight participants. Standard deviations are indicated in brackets.

Location	Step	Max GS (°)	Max IMU (°)	Min GS (°)	Min IMU (°)	Range GS (°)	Range IMU (°)
T1	20	14.28 (6.71)	13.23 (7.54)	-28.98 (10.26)	-29.96 (10.03)	43.26 (6.62)	43.18 (6.89)
	24	13.12 (7.45)	12.27 (7.32)	-29.76 (10.32)[AB]	-30.69 (9.92)[AB]	42.89 (6.98)	42.96 (7.50)
	28	12.87 (7.37)	12.93 (7.04)	-27.92 (10.47)[A]	-28.68 (10.24)[A]	40.79 (7.39)	41.61 (7.62)
	32	13.21 (7.30)	12.70 (7.29)	-25.63 (10.39)[B]	-26.83 (12.04)[B]	38.84 (10.08)	39.53 (9.88)
T7	20	38.61 (7.51)[CD]	39.56 (8.31)[CD]	-39.37 (8.94)	-39.52 (10.15)	77.98 (9.12)	79.08 (10.01)
	24	40.43 (6.65)[E]	41.32 (7.53)[E]	-39.87 (9.91)[GH]	-40.08 (10.92)[GH]	80.31 (9.27)	81.40 (10.07)
	28	41.50 (6.33)[CF]	42.55 (7.48)[C]	-37.62 (10.82)[G]	-38.04 (12.31)[G]	79.13 (9.22)	80.59 (10.12)
	32	42.92 (6.15)[DEF]	43.47 (7.56)[DE]	-36.02 (11.63)[H]	-36.60 (13.13)[H]	78.94 (10.57)	80.07 (11.63)
L1	20	36.88(6.79)	37.38 (7.25)	-35.81 (8.00)	-36.15 (7.86)	72.70 (7.97)	73.53 (8.63)
	24	37.89 (5.82)	38.57 (5.95)	-37.59 (9.15)	-37.91 (8.99)	75.48 (8.12)	76.48 (8.48)
	28	38.63 (5.01)	39.24 (5.11)	-36.12 (9.54)	-36.41 (9.61)	74.74 (7.58)	75.65 (8.03)
	32	39.32 (4.54)	39.71 (4.38)	-34.53 (10.77)	-34.99 (10.66)	73.85 (9.03)	74.70 (9.46)
S2	20	28.07 (8.25)	25.23 (6.53)	-29.67 (9.30)	-27.42 (12.07)	57.74 (12.53)	52.65 (17.10)
	24	26.80 (6.98)	24.22 (6.62)	-31.31 (8.69)	-29.91 (13.52)	58.11 (11.96)	54.14 (18.88)
	28	25.38 (6.19)	22.41 (6.91)	-30.10 (6.97)	-29.84 (10.22)	55.48 (9.26)	52.25 (15.75)
	32	27.42 (8.81)	25.88 (13.93)	-30.18 (7.46)	-27.73 (12.55)	57.60 (11.72)	53.61 (19.42)

[A]T1 Step 24 minima are significantly greater than Step 28 minima for GS (p = 0.002, d = 2.01 [large]) and IMU (p = 0.001, d = 2.37 [large])
[B]T1 Step 24 minima are significantly greater than Step 32 minima for GS (p = 0.009, d = 1.45 [large]) and IMU (p = 0.009, d = 1.44 [large])
[C]T7 Step 20 maxima are significantly smaller than Step 28 maxima for GS (p = 0.036, d = 1.57 [large]) and IMU (p = 0.046, d = 1.49 [large])
[D]T7 Step 20 maxima are significantly smaller than Step 32 maxima for GS (p = 0.008, d = 2.13 [large]) and IMU (p = 0.035, d = 1.58 [large])
[E]T7 Step 24 maxima are significantly smaller than Step 32 maxima for GS (p = 0.004, d = 2.41 [large]) and IMU (p = 0.043, d = 1.51 [large])
[F]T7 Step 28 maxima are significantly smaller than Step 32 maxima for GS (p = 0.041, d =1.52 [large])
[G]T7 Step 24 minima are significantly greater than Step 28 minima for GS (p = 0.03, d = 1.63 [large]) and IMU (p = 0.038, d = 1.00 [large])
[H]T7 Step 24 minima are significantly greater than Step 32 minima for GS (p = 0.017, d = 1.83 [large]) and IMU (p = 0.013, d = 1.31 [large])

Figure 1:

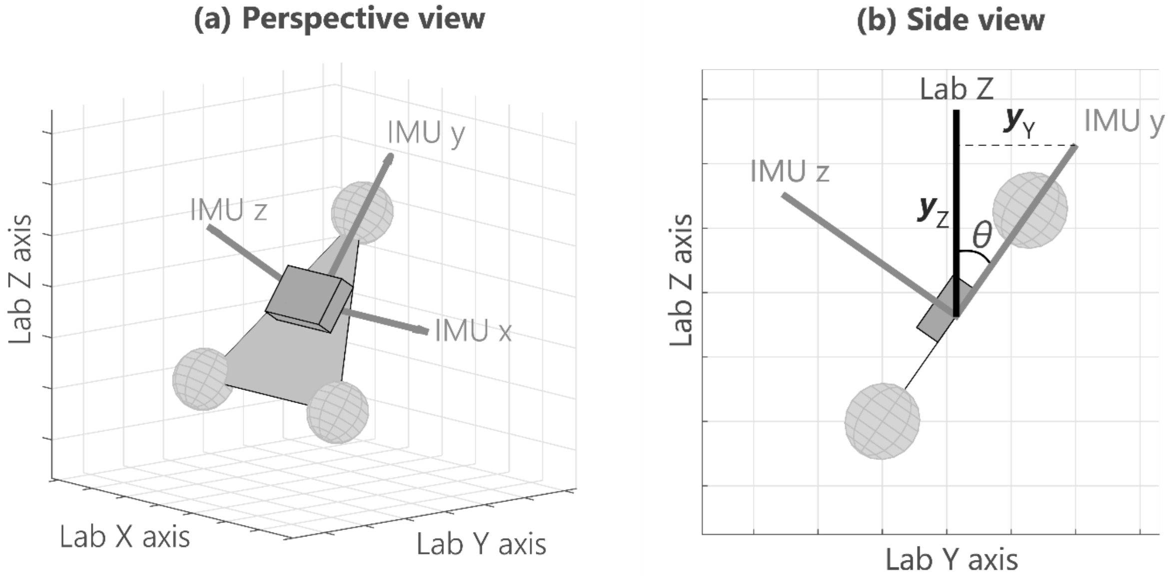


Figure 2:

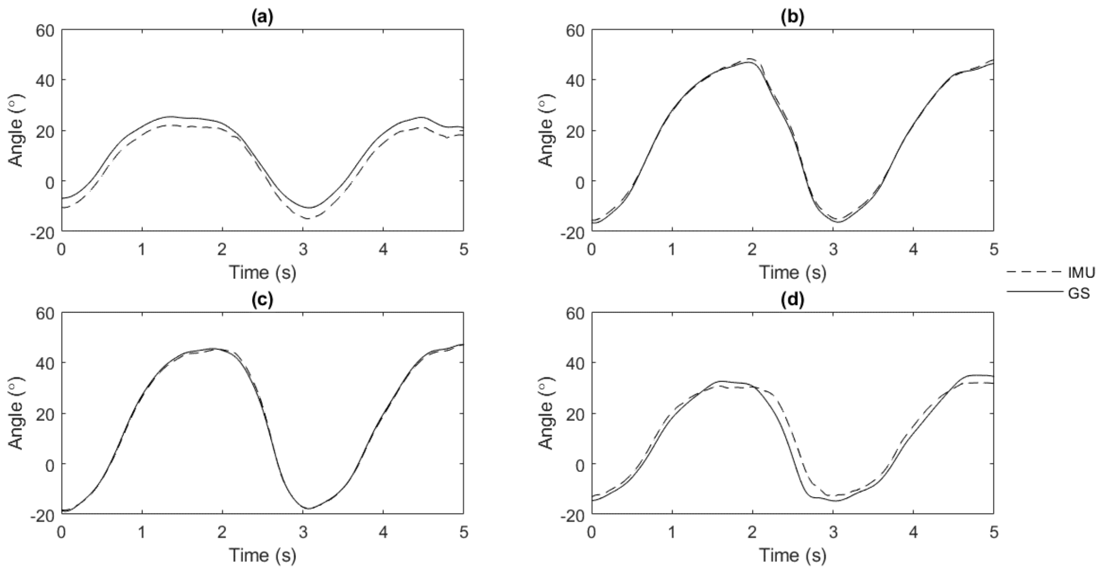


Figure 3:

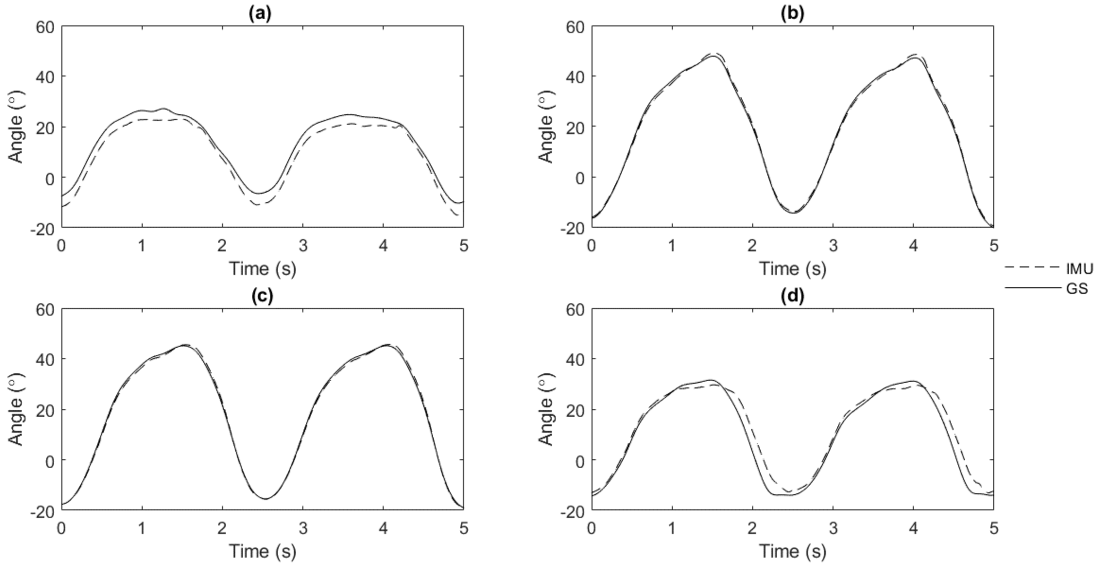
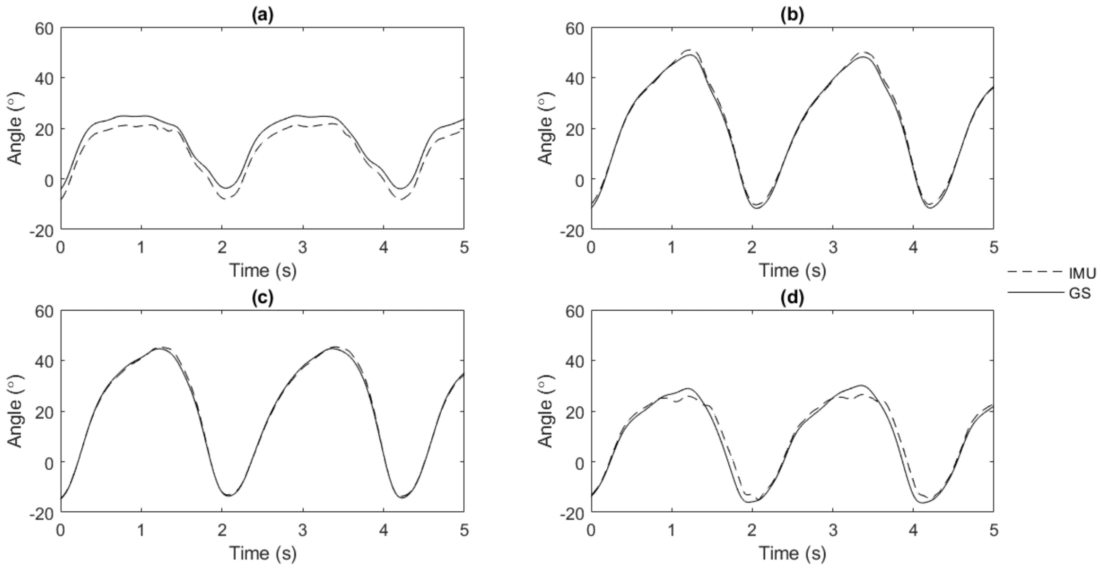


Figure 4:



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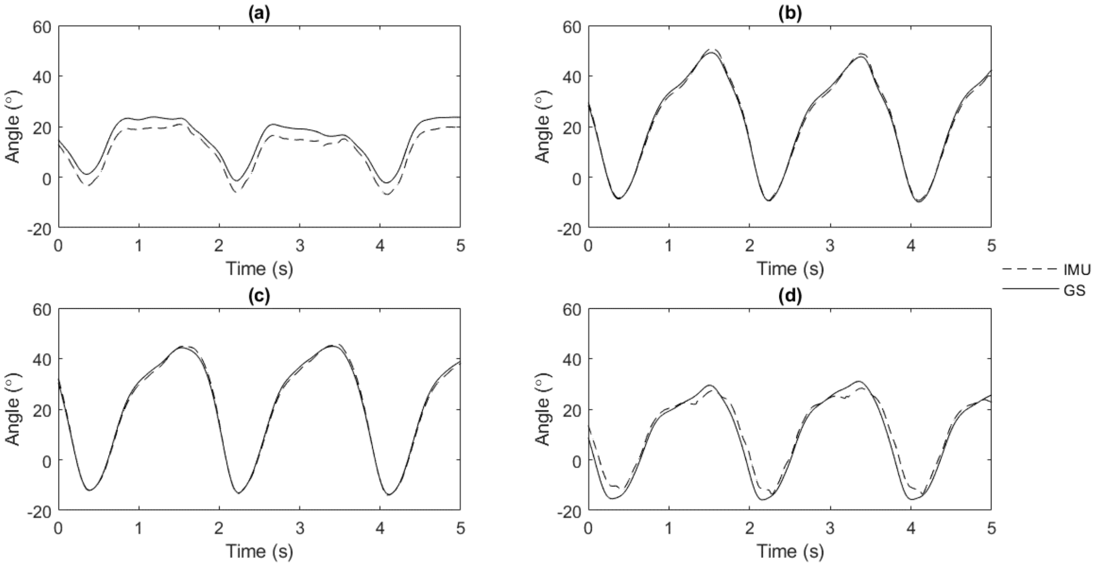

Figure captions:

Figure 1: Coordinate system used to analyse the orientation data, shown here in (a) 3D perspective and (b) the side view. The retro-reflective markers (grey circles) define the sensor's XY plane. We define the angle with respect to the vertical as the angle between the lab's Z axis and the sensor's Y axis, indicated here as θ.

Figure 2: The gold-standard (GS) angles and IMU angles at (a) T1 (RMSE = 3.04°), (b) T7 (RMSE = 1.02°, (c) L1 (RMSE = 0.71°), and (d) S2 (RMSE = 3.57°). This was for a stroke rate of 20 strokes per minute for one participant.

Figure 3: The gold-standard (GS) angles and IMU angles at (a) T1 (RMSE = 3.51°), (b) T7 (RMSE = 1.04°), (c) L1 (RMSE = 0.73°), and (d) S2 (RMSE = 3.54°). This was for a stroke rate of 24 strokes per minute for one participant.

Figure 4: The gold-standard (GS) angles and IMU angles at (a) T1 (RMSE = 3.65°), (b) T7 (RMSE = 1.10°), (c) L1 (RMSE = 0.83°), and (d) S2 (RMSE = 2.97°). This was for a stroke rate of 28 strokes per minute for one participant.

Figure 5: The gold-standard (GS) angles and IMU angles at (a) T1 (RMSE = 3.17°), (b) T7 (RMSE = 1.07°), (c) L1 (RMSE = 0.91°), and (d) S2 (RMSE = 3.65°). This was for a stroke rate of 32 strokes per minute for one participant.